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HAZARDOUS MATERIALS TRANSPORTATION*

by

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Abstract

This chapter is written in a tutorial style and its aim is to provide a comprehensive review of the literature on hazardous materials transportation. In Section 2, we offer a high-level view of hazmat logistics literature where we summarize special journal issues, reference books, reports and web sites that are potentially useful to an operations researcher who wishes to conduct research in this area. We also offer a classification of journal papers, which provides the organizational structure for the rest of the chapter. Section 3 contains a treatment of risk, the main ingredient of hazmat logistics problems that separate them from other logistics problems. We review different models of risk for hazmat transport and discuss how one can go from point risk to segment edge risk and then to route risk. Section 4 deals with hazmat routing and scheduling problems. In Section 5, we turn our attention to models that combine undesirable facility location and hazmat transportation. In the final section we offer a critique of the existing literature and suggest directions for future research.

Key words: hazardous materials, transportation, risk, optimization.

Résumé

Ce chapitre a été écrit dans un style pédagogique et son but est de donner un compte rendu global de la littérature qui existe sur le transport de matières dangereuses. Dans la section 2, on offre une vue de haut niveau sur la littérature de la logistique des matières dangereuses en résumant des journaux académiques spéciaux, des livres de référence, des rapports et des sites web qui peuvent être utiles à des chercheurs du domaines des opérations voulant faire des recherches dans ce domaine. On offre également une classification d'articles académiques sur laquelle se base l'organisation du reste du chapitre. La section 3 contient un traitement du risque. Celui-ci constitue l'essentiel des problèmes auxquels s'expose la logistique des matières dangereuses et les différencie des autres problèmes de logistique. On examine différents modèles de risque dans le transport des matières dangereuses tout en discutant comment développer un modèle de risque pour étudier un point donné, pour ensuite l'étendre dans le but d'inclure un segment de parcours et même un parcours entier. La section 4 traite les problèmes de programmation des itinéraires ainsi que des horaires du transport des matières dangereuses. Dans la section 5, l'attention est tournée vers des modèles qui combinent l'emplacement indésirable ainsi que le transport de matières dangereuses. Enfin, dans la dernière section, on analyse les textes existant sur ce sujet et propose des directives pour faire des recherches futures.

Mots clés : matières dangereuses, transport, risque, optimisation.

1. Introduction

The transportation of hazardous materials (or dangerous goods) deserves to be treated in a separate chapter of this volume, primarily due to the risks associated with this activity. Although the industry has an excellent safety record, accidents do happen, and the consequences can be significant, due to the nature of the cargo. Reduction of hazardous material (hazmat) transportation risks can be achieved in many different ways. Some of these risk reduction measures, such as driver training and regular vehicle maintenance, have little connection to operations research (OR), whereas others offer interesting challenges to OR. This chapter focuses on applications of OR models to hazmat transportation, providing a relatively comprehensive review of the literature, and outlining areas of potential impact for operations researchers.

According to the US Department of Transportation (US DOT), a hazardous material is defined as any substance or material capable of causing harm to people, property, and the environment. Dependence on hazardous materials is a fact of life in industrialized societies. There are thousands of different hazardous materials in use today (US DOT, 2004b). The United Nations sorts hazardous materials into nine classes according to their physical, chemical, and nuclear properties: explosives and pyrotechnics; gasses; flammable and combustible liquids; flammable, combustible, and dangerous-when-wet solids; oxidizers and organic peroxides; poisonous and infectious materials; radioactive materials; corrosive materials (acidic or basic); and miscellaneous dangerous goods, such as hazardous wastes (UN, 2001). In almost all instances, hazmats originate at a location other than their destination. For example, oil is extracted from oil fields and shipped to a refinery (typically via a pipeline); many oil products, such as heating oil and gasoline, are refined at the refinery and then shipped to storage tanks at different locations within a country. As another example, polychlorinated biphenyls (PCBs) are collected at many industrial installations, such as old power generation and transfer stations and shipped to a special waste management facility for safe disposal (usually incineration). Hence, transportation plays a significant role for hazmats. The magnitude of this role depends on the size of a country and its level of industrialization. For example, the Office of Hazardous Materials Safety (OHMS) of the US DOT estimated that there were 800,000 domestic shipments of hazmats, totalling approximately 9 million tons, in the USA each day in 1998 (US DOT, 2000). Transport Canada estimates that nearly 80,000 shipments of dangerous goods are moved by road, rail, water and air in Canada (Transport Canada, 2004). Given a conservative estimate of 2% annual growth in the production of hazmats, it is safe to assume that the total number of shipments in North America is well over the one million mark in 2005.

In 2002, over 99 percent of hazmat shipments in Canada made it safely to their destination (Transport Canada, 2004). While the hazmat transport sector is far safer than other transport sectors (US DOT, 2000), hazmat transport accidents do happen. Figure 1.1 shows the distribution of accidents/incidents by hazmat class in 2003. An accident resulting in a release of the hazmat is called an incident. The figure shows that flammable-combustible liquids and corrosive materials accounted for the majority of hazmat accidents/incidents in the USA (US DOT, 2004a).

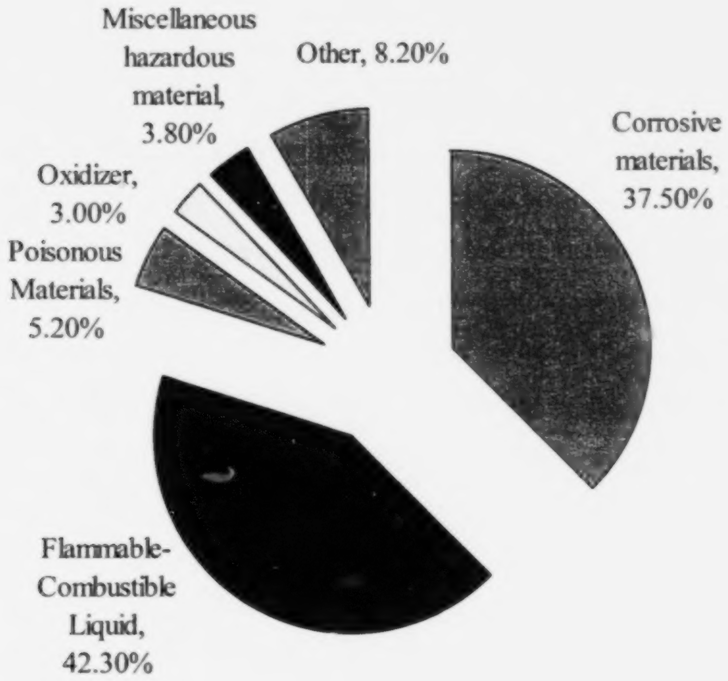


Figure 1.1: Accident/incident by hazmat class in 2003 (US DOT, 2004a)

The transportation of hazmats can be classified according to the mode of transport, namely: road, rail, water, air, and pipeline. Some shipments are intermodal; they are switched from one mode to another during transit. There are significant differences in the use of these modes. While transportation by truck accounts for approximately 94% of all individual hazmat shipments in the USA, this mode carries merely 43% of the hazmat tonnage since the volume that can be shipped by one truck is limited compared to other modes of transport. In contrast, rail, water, and pipelines carry 57% of the hazmat tonnage while accounting for less than 1% of all individual shipments. It is possible to carry huge quantities of hazmats using these modes. While the counting of individual shipments is less clear with these modes (How do we count the number of shipments via a pipeline? Does a train consisting of multiple hazmat tank cars count as a single shipment?), they carry much larger quantities per shipment than trucks do. The balance of hazmat shipments (5% by count and 0.05% by weight) are made via air (US DOT, 1998).

Hazmat transport incidents can occur at the origin or destination (when loading and unloading) or en-route. Incidents involving hazmat cargo can lead to severe consequences characterized by fatalities, injuries, evacuation, property damage, environmental degradation and traffic disruption. In 2003, there were 488 serious incidents (among a total of 15,178 incidents) resulting in 15 deaths, 17 major and 18 minor injuries, and a total property damage of $37.75 million (US DOT, 2004c). About 90% of hazmat incidents occur on highways. As far as causes go, human error seems to be the single greatest factor (see Figure 1.2) in all hazardous materials incidents (minor and serious incidents).

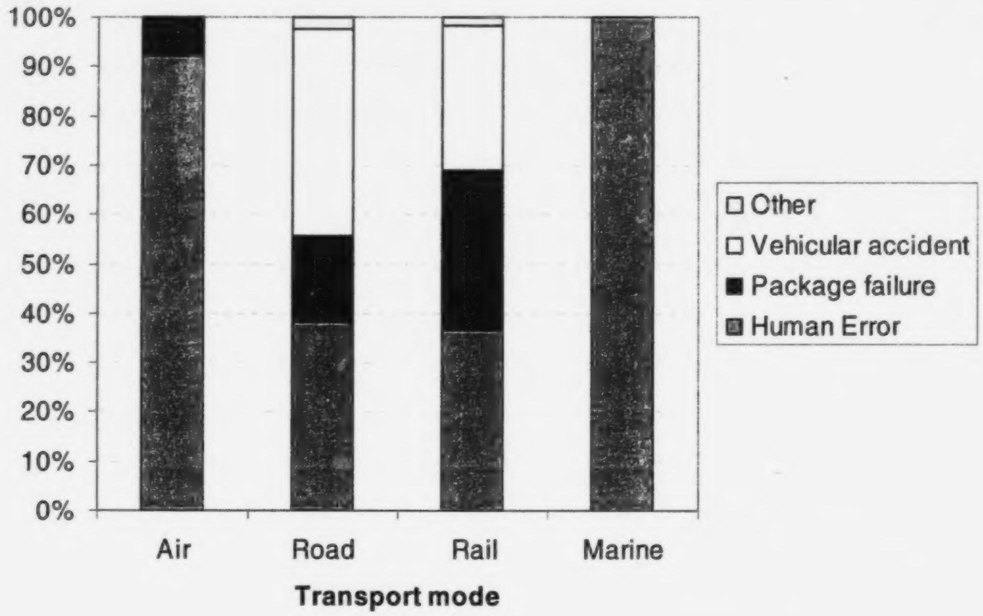


Figure 1.2: Serious incident by mode/cause in 2003 (US DOT, 2004c)

The annual number of non-hazmat transportation accidents in the USA is estimated to be 126,880, in contrast to the approximately 15,000 hazmat transportation accidents and incidents (FMCSA, 2001). Even though hazmats are involved in a small minority of all transport accidents, hazmat accidents can have catastrophic consequences. In 2003, for example, 22 train cars derailed at Tamoroa, IL, resulting in the release of various types and quantities of hazardous materials from seven tank cars. The evacuation of over a thousand residents within a three-mile radius and the closing of Highway 51 followed the derailment.

Table 1.1 contrasts the average costs (per event) of hazmat and non-hazmat motor carrier accidents and incidents for one year. Although the cost of an average hazmat incident is not significantly higher than the cost of a non-hazmat incident, the cost of a hazmat incident resulting in fire or explosion is significantly higher. Hazmat transportation accidents are perceived as low probability-high consequence (LPHC) events and data seem to support this perception. For example, chlorine leaking from damaged tank cars due to a derailment in Mississauga, Ontario in 1979, forced the evacuation of 200,000 people. In 1982, a gasoline truck explosion in a tunnel in Afghanistan caused 2,700 fatalities. Most transport accidents that impact a large number of people and result in significant economic loss involve a hazmat cargo.

Table 1.1: Comparative costs of hazmat and non-hazmat motor carrier accident/incident events (FMCSA, 2001)

Type of accident/incident event	Average cost (in US $)	Average traffic delay (in hours)
Non-hazmat events	340,000	2
All hazmat events	414,000	-
Hazmat events with spill/release	536,000	5
Hazmat events with fire	1,200,000	8
Hazmat events with explosion	2,100,000	12

Hazmat transportation involves multiple players such as shippers, carriers, packaging manufacturers, freight forwarders, consignees, insurers, governments, and emergency responders; each has a different role in safely moving hazardous materials from their origins to their destinations. There are often multiple handoffs of material from one party to another during transport. The various parties, ranging from individuals or small firms to large multinational organizations, may have overlapping and unclear responsibilities for managing the risks (ICF Consulting, 2000). Furthermore, each party may have different priorities and viewpoints. Although the transportation department or local government is responsible for designating allowable routes that reduce risk, a carrier company would, in general, try to identify the route that minimizes the, fuel costs, and travel times, between the origin and destination for each shipment. Some routes have short lengths but move through heavily populated areas; some routes avoid heavily populated areas but are longer, resulting in higher transport costs and accident probabilities; while other routes use major freeways and thus minimize travel time but may be associated with higher accident rates. Thus, hazmat transportation is a typical multiobjective problem with multiple stakeholders.

Multiobjective/multi stakeholder problems are complicated to solve. Hazmat transport problems are further complicated by public sensitivity surrounding these problems. Given the low probability/high consequence nature of hazmat-related incidents, and the involuntary nature of the associated risks, public reaction to such accidents is much stronger than to non-hazmat incidents. Almost every hazmat accident appears on front pages of newspapers and on television news and results in a call for action, such as tighter transport regulations or even the banning of hazmats, in some extreme cases.

Public sensitivity to hazmat transport is rooted not only in public risk perceptions, but also in equity concerns. Those individuals benefiting from hazmat shipments are usually those who live near the production facility or the delivery points. Yet the population living along a major highway connecting the hazmat origin and destinations is exposed to the transport risks regardless of whether or not they benefit from the hazmat shipments. This lack of burden-benefit concordance is another source of public opposition to hazmat shipments. The shipment of spent nuclear fuel rods from nuclear power plants to the proposed repository at Yucca Mountain in Nevada, USA, offers a good example of equity-based public opposition. The shipping reduces the risk at the power plants. Yet some risk is imposed on the population living along the major east-west highways or railways, who are asked to assume the risk with no clear benefits to them. Furthermore, if the same main route segment were selected for shipments from multiple origins, the objection of people living along this route would increase considerably. These people are likely to prefer alternate routings that would spread the risks.

Public opposition to hazmat shipments has increased in recent years, due to fears of terrorist attacks on hazmat vehicles. The Research and Special Projects Administration (RSPA) of US DOT accepts that hazmats could pose a significant threat during transportation, when they are particularly vulnerable to sabotage or misuse as weapons of mass destruction or as weapons of convenience by terrorists—particularly given how easy it is to identify a hazmat vehicle (as well as the specifics of their cargo) given the current system of hazmat placards. As a result some jurisdictions are trying to force a rerouting of hazmat vehicles away from populated areas by implementing local laws.

Much of the discussion to this point also applies to the location of hazardous facilities. If anything, the risks and the public opposition are higher for fixed facilities than for transport. Operations researchers have dealt with both types of problems, and we will include references to facility location as well as transportation problems in this chapter, particularly for facility location models that treat the transportation component explicitly.

The rest of this chapter is organized in the following way. In Section 2, we offer a high-level view of hazmat logistics literature where we summarize special journal issues, reference books, reports and web sites that are potentially useful to an operations researcher who wishes to conduct research in this area. We also offer a classification of journal papers, which provides the organizational structure for the rest of the chapter. Section 3 contains a treatment of risk, the main ingredient of hazmat logistics problems that separate them from other logistics problems. We review different models of risk for hazmat transport and discuss how one can go from point risk to edge risk and then to route risk. Section 4 deals with hazmat routing and scheduling problems. In Section 5, we turn our attention to models that combine undesirable facility location and hazmat transportation. In the final section we offer a critique of the existing literature and suggest directions for future research.

2. A high-level view of hazmat logistics research

2.1 Special issues of journals

Hazmat logistics has been a very active research area during the last twenty years. In 1984 *Management Science* published a special issue on Risk Analysis (Vol. 30, No. 4) where five papers dealt with hazmats and hazardous facilities. This was followed by a number of special issues of refereed academic journals that focus on hazmat transportation or location problems.

- *Transportation Research Record* published two special issues on hazmat transportation in 1988 (No. 1193) that included four papers and 1989 (No. 1245) that includes six papers.
- *Transportation Science* devoted an issue to hazmat logistics in 1991 (Vol. 25, No. 2) that contained six papers.
- There was a special section on hazmat transportation in the March/April 1993 issue of the *Journal of Transportation Engineering* that included four papers.
- A special double-issue of *INFOR* on hazardous materials logistics was published in 1995 (Vol. 33, No. 1 and 2) with nine papers.
- Four papers were included in a special issue of *Location Science* dealing with hazmats in 1995 (Vol. 3, No. 3).
- *Transportation Science* produced a second special issue on hazmat logistics in 1997 (Vol. 31, No. 3) with seven papers.
- *Studies in Locational Analysis* published a special issue on undesirable facility location in April 1999 (Issue 12) that contained seven papers.
- *Computers & Operations Research* will publish a hazmat logistics special issue in 2007 which will contain results of the most recent research in the area in 13 papers.

These special issues contain many useful papers and they offer a good starting point for research in this area. Likewise, the book chapter by Erkut and Verter (1995a) offers a relatively comprehensive survey of the literature up to 1994, and the annotated bibliography by Verter and Erkut (1995) offers a good list of pre-1994 references in risk assessment, location, and routing.

2. 2 Books

Perhaps an even better starting point for those who wish to familiarize themselves with the terminology and the problem context are the following books.

- *Transportation of Hazardous Materials: Issues in Law, Social Science, and Engineering* (1993), edited by L. N. Moses and D. Lindstrom, Kluwer Academic Publishers. This book contains 18 articles presented at *Hazmat Transport '91*, a national conference held at Northwestern University on all aspects of hazmat transport. While only a few of the articles use OR models and techniques, the book offers a multi-dimensional treatment of the subject and it is good reading for new researchers in the area.
- Three books were produced by Institute for Risk Research, University of Waterloo, as a result of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held in Toronto, Canada in April, 1992:
  - *Transportation of Dangerous Goods: Assessing the Risks* (1993), edited by F.F. Saccomanno and K. Cassidy. This book contains 30 articles which are organized into five main chapters: Application of QRA models to the transport of Dangerous Goods; Analysis of Dangerous Goods Accident and Releases; Application of Simple Risk Assessment Methodology; Uncertainty in Risk Estimation; Risk Tolerance, Communication and Policy Implications.
  - *Comparative Assessment of Risk Model Estimates for the Transport of Dangerous Goods by Road and Rail* (1993), edited by F.F. Saccomanno, D. Leming, and A. Stewart. This book documents the assessment of a corridor exercise involving the application of several risk models to a common transport problem involving the bulk shipment of chlorine, LPG and gasoline by road and rail along predefined routes. The purpose

  of the corridor exercise was to provide a well defined transportation problem for analysis in order to examine the sources of variability in the risk estimates. Seven agencies in six countries participated in this exercise.

  - *What is the Risk* (1993), edited by F.F. Saccomanno, D. Leming, and A. Stewart. This book documents the small group discussions and consensus testing process from the corridor exercise conducted as part of the international consensus conference.

- *Hazardous materials transportation risk analysis: quantitative approaches for truck and train* (1994), Rhyne WR, Van Norstrand Reinhold, 1994. This book explains the quantitative risk analysis (QRA) methodologies and their application to hazmat transportation. It also provides an extended example of a QRA for bulk transport of chlorine by truck and train. This detailed example explores every step of the QRA from preliminary hazards analysis to risk reduction alternatives. This book is a valuable reference for hazmat transportation risks, and it is intended for practitioners. It is not an OR book, but it provides useful information for OR research in hazmat transportation modeling and analysis.
- *Guidelines for chemical transportation risk analysis* (1995), American Institute of Chemical Engineers, Center for Chemical Process Safety (CCPS), New York. This book completes two other books in the series of process safety guidelines books produced by CCPS: Guidelines for Chemical Process Quantitative Risk Analysis (CPQRA, 1989) and Guidelines for Hazard Evaluation Procedures (HEP, 2nd edition, 1992). It is intended to be used as a companion volume to the CPQRA and HEP Guidelines when dealing with a quantitative transportation risk analysis (TRA) methodology. This book offers a basic approach to TRA for different transport modes (pipelines, rail, road, barge, water, and intermodal containers). It can be useful to an engineer or manager in identifying cost effective ways to manage and reduce the risk of a hazmat transportation operation.

- *Quantitative Risk Assessment of Hazardous Materials Transport Systems* (1996), M. Nicolet-Monnier and A.V. Gheorge, Kluwer Academic Publishers. This book contains a comprehensive treatment of the analysis and assessment of transport risks due to hazmat transport on roads, rail, by ship, and pipeline. It contains European case studies as well as a discussion of computer-based DSS (Decision Support System) for hazmat transport problems. It is a useful reference book in the area.

2. 3 Reports

In addition to these books, there are also a number of recent government reports that contain a wealth of useful information for researchers in OR as well as other relevant fields:

- *AND-DIS-01-1 A National Risk Assessment for Selected Hazardous Materials in Transportation* (2000) (download from http://www.dis.anl.gov/ep/ca/ep_ca_home.html), Argonne National Laboratory, Department of Energy.
- *ANL-DIS-00-1: Development of the Table of Initial Isolation and Protective Action Distances for the 2000 Emergency Response Guidebook* (2000), (download from http://www.dis.anl.gov/ep/ca/ep_ca_home.htm!), Argonne National Laboratory, Department of Energy.
- *Comparative Risks of Hazardous Materials and non-hazardous materials Truck Shipment Accidents/Incident (2001),* Batelle (download from http://hazmat.dot.gov/risk_analyses.htm)
- *A Resource Handbook on DOE Transportation Risk Assessment* (2002), DOE Transportation Risk Assessment Working Group Technical Subcommittee, (download from www.ntp.doe.gov/transrisk_handbook.pdf)

(Note: All URLs in this chapter were functional as of May 2005.)

2.4 Web Sites

The following web sites contain useful information for practitioners as well as researchers on hazmat transport:

- The Office of Hazardous Materials Safety (US DOT Research and Special Programs Administration): http://hazmat.dot.gov/
- The Hazmat 101 Web: http://www.hazmat101.com/
- Hazmat Magazine: http://www.hazmatmag.com/
- On-line hazmat school: http://www.hazmatschool.com/
- National Hazardous Materials Route Registry: http://hazmat.fmcsa.dot.gov/info.html
- United Nations Economic Commission for Europe (UNECE) – Dangerous Goods and Special Cargo: http://www.unece.org/trans/danger/danger.htm
- The Canadian Transport Emergency Centre (CANUTEC) of the Department of Transport: http://www.tc.gc.ca/canutec/
- A mailing list for those interested in hazmat transport: http://groups.yahoo.com/group/DangerousGoods/

2.5 Software

There exists some software which has been developed to aid the analysts or decision makers in dealing with hazmat logistics. For example, ALOHA (Areal Locations of Hazardous Atmospheres) predicts how a hazardous gas cloud might disperse in the atmosphere after an accidental chemical release. This software (see US EPA, 2004) has been developed jointly by the National Oceanic and Atmospheric Administration's (NOAA) Hazardous Materials Response and Assessment Division and the U. S. Environmental Protection Agency's (EPA) Chemical Emergency Preparedness and Prevention Office. ALOHA can be useful for transport risk assessment. However, this software is more useful for fixed facility risk assessment than for route selection.

In contrast to the availability of many software packages for regular truck routing, we know of only one off-the-shelf hazmat routing package that is currently available:

PC*Miler|HazMat (ALK Associates, 1994). It has features that allow transportation and logistics companies to determine routes and mileages for hauling hazardous materials while ensuring compliance with government regulations. Routes can be generated for general, explosive, inhalant and radioactive hazmats. This software contains all of the features and functionality of PC*Miler, a routing, mileage and mapping software, which is also developed by ALK. Here we note that HazTrans (Abkowitz et al, 1992) and PC*HazRoute (ALK Associates, 1994) were marketed in the last decade, but both are off the market as of 2005.

2. 6 Classification

While we offer references to books, reports, and web sites in this section, the rest of this chapter deals mainly with the academic literature consisting of refereed journal articles. Figure 2.1 displays the number of papers published in this area between 1982 and 2004. It seems that this area of research has peaked in mid 1990s and has declined somewhat since.

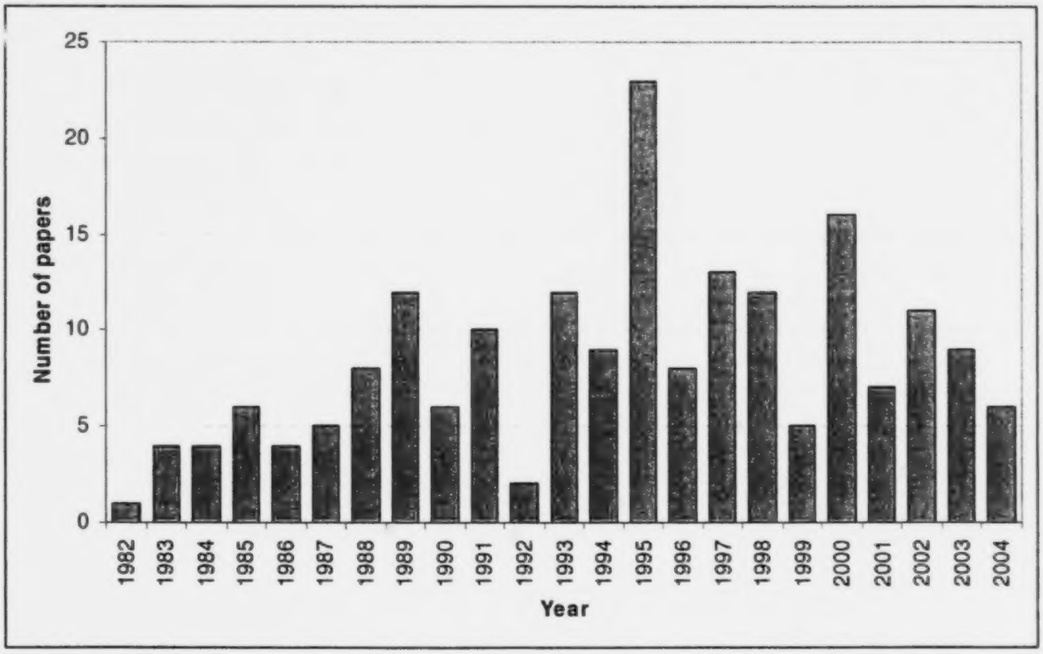


Figure 2.1. Number of hazmat related papers published in refereed journals between 1982 and 2004.

Given the large number of papers in this area, we believe a simple classification can be useful in providing some structure to the rest of the chapter. The articles in this area deal with different aspects of the problem. One possible classification is the following (in no particular order):

1. Risk assessment,
2. Routing,
3. Combined facility location and routing,
4. Network design.

Although we have offered this simple classification, it is fair to say that numerous papers deal with problems that lie at the intersection of the above areas and such problems are receiving increasingly more attention in the literature.

Table 2.1 provides a classification of papers using the above four problem classes as well as other important attributes such as transport mode, paradigm (deterministic vs. stochastic) and number of objectives, and whether or not the paper uses GIS (Geographic Information System) or proposes a DSS.

Table 2.1. A Classification of Hazmat Transportation Models

C: with security consideration ; DSS: Decision Support System model ; G: using GIS ; M: Multiobjective ; S: Stochastic ; T: Time-varying ; U: Survey/Annotated Bibliography

Risk assessment	Road	Jonkman, *et al.* (2003), Nardini *et al.* (2003), Martinez-Alegria *et al.* (2003)^{G}, Rosmuller and Van Gelder (2003), Abkowitz (2002)^{C}, Fabiano *et al.* (2002), Kimberly and Killmer (2002), Saccomanno and Haastrup (2002)$^{\text{tunnels}}$, Hollister (2002), Hwang *et al.* (2001), Abkowitz *et al.* (2001), Verter and Kara (2001)^{G}, Efroymson and Murphy (2000), ICF Consulting (2000), Leonelli *et al.* (1999), Zhang *et al.* (2000)^{G}, Pet-Armacost *et al.* (1999), Cassini (1998), Mills and Neuhauser (1998), Cutter and Ji (1997), Groothuis and Miller (1997), Lovett *et al.* (1997)^{G}, Pine and Marx (1997), Alp and Zelensky (1996), Ertugrul (1995), Sissell (1995), Chakraborty and Armstrong (1995), Erkut and Verter (1995a)^{U}, Erkut and Verter (1995b), Moore *et al.* (1995)^{G}, Spadoni *et al.* (1995), Verter and Erkut (1995)^{U}, Gregory and Lichtenstein (1994), Macgregor *et al.* (1994), Hobeika and Kim (1993), Sandquist *et al.* (1993), Harwood *et*

		al. (1993), Abkowitz *et al.* (1992), Glickman (1991), Grenney, *et al.* (1990)^{DSS}, Kunreuther and Easterling (1990), Chow *et al.* (1990), Abkowitz and Cheng (1989), Ang *et al.* (1989), Harwood *et al.* (1989), Abkowitz and Cheng (1988), Hillsman (1988), Horman (1987), Keeney and Winkler (1985), Scanlon and Cantilli (1985), Pijawka *et al.* (1985), Kunreuther, *et al.* (1984), Philipson, *et al.* (1983), Wilmot *et al.* (1983), Keeney (1980), Shappert *et al.* (1973)	
	Rail	Anderson and Barkan (2004), Barkan *et al.* (2003), Fronczak (2001), Orr *et al.* (2001), Dennis (1996), Larson (1996), Glickman and Golding (1991), McNeil and Oh (1991), Saccomanno and El-Hage (1991), Glickman and Rosenfield (1984), Glickman (1983), Saccomanno and El-Hage (1989)	
	Marine	Douligeris, *et al.* (1997), Roeleven *et al.* (1995), Romer *et al.* (1995)	
	Air	LaFrance-Linden *et al.* (2001)	
	Road + Rail	Brown and Dunn (2005), Milazzo *et al.* (2002), Bubbico *et al.* (2000), Neill and Neill (2000), Deng *et al.* (1996), Leeming and Saccomanno (1994), Purdy (1993), Saccomanno, and Shortreed (1993), Saccomanno, *et al.* (1989), Vanaerde *et al.* (1989), Glickman (1988), Swoveland (1987)	
	Road + Rail + Marine	Andersson (1994)	
	Road + Rail + Marine + Air	Kloeber *et al.* (1979)	
Routing	Local Routing	Road	Akgün, *et al.* (2005), Duque, *et al.* (2005), Erkut and Ingolfsson (2005), Huang and Cheu (2004)$^{C, G}$, Huang, *et al.* (2003)$^{C, M}$, Kara *et al.*(2003), Luedtke and White (2002)$^{C, U}$, Marianov *et al.* (2002), Frank *et al.* (2000), Erkut, and Ingolfsson (2000), Leonelli, et.al. (2000), Zografos, *et al.* (2000)^{DSS}, Erkut, and Verter (1998), Tayi *et al.* (1999)^{M}, Bonvicini *et al.* (1998), Marianov and ReVelle (1998)^{M}, Verter and Erkut (1997), Sherali *et al.* (1997)^{M}, Nembhard and White (1997)^{M}, Erkut and Glickman (1997), Jin and Batta (1997), Verter and Erkut (1997), Erkut (1996), Jin *et al.* (1996), Ashtakala and Eno (1996)^{S}, Beroggi and Wallace (1995), Boffey and Karkazis (1995), Erkut (1995), Moore *et al.* (1995)^{G}, Karkazis and Boffey (1995), Glickman and Sontag (1995)^{M}, McCord and Leu (1995)^{M}, Sivakumar *et al.* (1995), Beroggi (1994), Beroggi and Wallace (1994), Ferrada and Michelhaugh (1994), Patel and Horowitz (1994)^{G}, Lassarre *et al.* (1993)^{G}, Sivakumar *et al.* (1993), Turnquist (1993)$^{M, S}$, Wijeratne *et al.* (1993)^{M}, Lepofsky *et al.* (1993)^{G}, Beroggi and Wallace (1991), Miaou and Chin (1991), Gopalan *et al.* (1990a), Chin

			and Cheng (1989)^{M}, Zografos and Davis (1989)^{M}, Abkowitz and Cheng (1988)^{M}, Batta and Chiu (1988), Vansteen (1987), Cox, and Turnquist (1986), Belardo, *et al.* (1985), Saccomanno and Chan (1985), Urbanek and Barber (1980), Kalelkar and Brinks (1978)^{M}
		Rail	Verma and Verter (2005), McClure *et al.* (1988), Coleman (1984), Glickman (1983)
		Marine	Iakovou (2001), Li *et al.* (1996), Haas and Kichner (1987)
		Road + Rail	Glickman (1988)
		Road + Rail + Marine	Weigkricht and Fedra (1995)^{DSS}
	Local Routing and Scheduling (on Road)	Zografos and Androutsopoulos (2004)^{M}, Zografos and Androutsopoulos (2002)^{M}, Miller-Hooks and Mahmassani (2000)^{S,T}, Bowler and Mahmassani, (1998)^{T}, Miller-Hooks and Mahmassani (1998)^{S,T}, Sulijoadikusumo and Nozick (1998)^{M,T}, Nozick, *et al.* (1997)^{M,T}, Smith (1987)^{M}, Cox and Turnquist (1986)	
	Global Routing	Road	Carotenuto, et al. (2005a,b), Dell'Olmo et al. (2005), Akgün et al. (2000), Marianov and ReVelle (1998), Lindner-Dutton et al. (1991), Gopalan et al. (1990a, b), Zografos and Davis (1989)
		Marine	Iakovou et al. (1999)
Combined Facility Location and Routing	Alumur and Kara (2005), Cappanera *et al.* (2004), Berman, et el. (2000), Giannikos (1998)^{M}, Helander and Melachrinoudis (1997), List and Turnquist (1998), Current and Ratick (1995)^{M}, Jacobs and Warmerdam (1994), Boffey and Karkazis (1993), Stowers and Palekar (1993), List and Mirchandani (1991)^{M}, List, *et al.* (1991)^{U}, Revelle *et al.* (1991), Zografos and Samara (1989), Peirce and Davidson (1982), Shobrys (1981)		
Network Design	Erkut and Gzara (2005), Erkut and Alp (2005), Verter and Kara (2005), Berman et al. (2005), Kara and Verter (2004)		

The rest of this chapter provides a comprehensive literature survey following the problem classification presented above, and points out directions for future research.

3. Risk assessment

Risk is the primary ingredient that separates hazmat transportation problems from other transportation problems. In this section we will provide a detailed treatment of how risk is incorporated into hazmat transport models, starting with the basic building blocks and moving our way into risk assessment along a route. In the context of hazmat transport, risk is a measure of the probability and severity of harm to an exposed receptor due to potential undesired events involving a hazmat (Alp, 1995). The exposed receptor can be a person, the environment, or properties in the vicinity. The undesired event in this context is the release of a hazmat due to a transport accident. The consequence of a hazmat release can be a health effect (death, injury, or long-term effects due to exposure), property loss, an environmental effect (such as soil contamination or health impacts on flora and fauna), an evacuation of nearby population in anticipation of imminent danger, or stoppage of traffic along the impacted route.

Risk assessment can be qualitative or quantitative. Qualitative risk assessment deals with the identification of possible accident scenarios and attempts to estimate the undesirable consequences. It is usually necessitated by a lack of reliable data to estimate accident probabilities and consequence measures. The goal is to identify events that appear to be most likely and those with the most severe consequences, and focus on them for further analysis. It may be the only option in the absence of data—for example assessing the risks due to the location of a permanent nuclear waste repository. While hazmat transport analysts are known to complain about the quality of their data (we will return to this topic later in this section), they do have access to considerable historical information on accident frequencies and fairly accurate consequence models for hazmat releases in case of accidents in many developed countries. Due to this, and the necessity of quantitative information for OR models, in this section we focus on quantitative risk assessment.

Quantitative risk assessment (QRA) involves the following key steps: (1) Hazard and exposed receptor identification; (2) Frequency analysis; and (3) Consequence modelling and risk calculation. Identification of hazard refers to identifying the potential sources of release of contaminants into the environment, the types (e.g., thermal radiation due to jet and pool fires and fireballs, explosions, flying pieces of metals or other objects due to blast waves, toxic clouds, and flame) and quantities of compounds that are emitted or released, and the potential health and safety effects associated with each substance. In some cases (for example when a release of carcinogenic substances is involved), we also need to investigate the long-term health risks of a hazmat accident. Examination of risks on different types of exposed receptor is also essential to cover different response characteristics in the risk assessment.

The language of QRA is one of *frequencies* and *consequences*, and unlike in qualitative risk analysis, QRA results in a numerical assessment of risks involved, for example an expected number of individuals impacted per year. In the next two subsections we discuss frequency analysis and consequence modelling along with risk calculation.

3.1 Frequency analysis

The frequency analysis involves (a) determining the probability of an undesirable event; (b) determining the level of potential receptor exposure, given the nature of the event; and (c) estimating the degree of severity, given the level of exposure (Ang *et al.*, 1989). Each stage of this assessment requires the calculation of a probability distribution, with stage (b) and (c) involving conditional distributions. Consider a unit road segment. Suppose that there is only one type of accident, release, incident, and consequence. Let A be the accident event that involves a hazmat transporter, M the release event, and I the incident event. Suppose that the consequence of the hazmat release is expressed in terms of the number of injuries. We denote the event of an injury to an individual as D. Using *Bayes' theorem*, we obtain the probability of an injury resulting from an accident related to the hazmat as:

$$\begin{aligned} p(A,M,I,D) &= p(D|A,M,I)p(A,M,I) \\ &= p(D|A,M,I)p(I|A,M)p(A,M) \\ &= p(D|A,M,I)p(I|A,M)p(M|A)p(A), \end{aligned} \tag{3.1}$$

where $p(E)$denotes the probability of the event E occurring on the road segment and $p(E|F)$ the associated conditional probability. Despite its simplicity, the above model already contains many of the necessary elements for hazmat risk assessment. For example, Chow *et al.* (1990) used a Bayesian model that includes multiple levels of event severity to predict severe nuclear accidents and to estimate the associate risks. Glickman (1991) used a Bayesian model in the assessment of the risks of highway transportation of flammable liquid chemicals in bulk.

Furthermore, let s_{lm} denote the number of shipments of hazmat m on road segment l per year. Note that a highway transport route from the origin to the destination consists of finitely many road segments. The product $s_{lm} p_l(A, M_m, I, D)$ determines the frequency of the occurrence of the hazardous release event that measures the *individual risk* for a person in the neighborhood of road segment l. Usually, the individual risk is defined as the yearly death frequency for an average individual at a certain distance from the impact area (see e.g. Mumpower, 1986 and Leonelli, *et al.* 2000). Although no universally accepted individual risk criteria exist, one tends to compare the risk of death to *de minimis* of 10^{-6} to 10^{-5} deaths per year (Mumpower, 1986).

Hazmat incidents usually impact a number of individuals. Hence, we need to move from individual risk towards *societal risk*. The societal risk is a characteristic of the hazardous activity in combination with its populated surroundings. There are several ways to express societal risk. Perhaps the simplest method is to compute the expected number of impacted individuals by multiplying the probability of impact per person with the number of persons present in the impact zone. Hence, the societal risk (or just *risk* for short) on road segment l of hazmat m, R_{lm}, can be expressed as

$$R_{lm} := s_{lm} \iint_L p_l(D_{xy}|A, M_m, I) p_l(I|A, M_m) p_l(M_m|A) p_l(A) POP_l(x,y)\, dx\, dy \tag{3.2}$$

where $p_l(D_{xy}|A, M_m, I)$ is the probability that individuals on location (x, y) in the impact area L will be dead due to the incident on a route segment l and $POP_l(x, y)$ is the population density on location (x, y) in the neighbourhood of road segment l. By assuming that each individual in the affected population will incur the same risk, R_{lm} can be simply expressed as

$$R_{lm} := s_{lm} p_l(D|A, M_m, I) p_l(I|A, M_m) p_l(M_m|A) p_l(A) POP_l \qquad (3.3)$$

Thus, if few people are present around the hazardous activity, the societal risk may be close to zero, whereas the individual risk may be quite high.

While this expected consequence is a convenient measure for OR models, the risk assessment literature prefers a richer measure, namely the *FN*-curve which expands the point estimate of the expectation to the entire distribution. To produce an *FN*-curve, one has to compute the probability that a group of more than *N* persons would be impacted due to a hazmat accident, for all levels of *N*. The risk level is communicated by the *FN*-curve, a graph with the ordinate representing the cumulative frequency distribution *F* of the hazardous release events which result in at least *N* number of impacts (e.g., number of fatalities or number of people evacuated) and abscissa representing the consequence (*N* impacts). Furthermore, if *F* is a conditional cumulative frequency distribution, then the associated *FN*-curve is called the *conditional FN*-curve. Figure 3.1 shows a conditional *FN*-curve for PCB transport through Edmonton, Canada (Erkut and Verter, 1995). The ordinate *F* is the annual cumulative frequency of incidents with at least *N* evacuations conditioned on the occurrence of an evacuation incident in the city. This figure shows that if an evacuation incident occurs, then the probability of evaucating more than 500 people is 0.8. Some countries (such as Denmark, Netherlands and the UK) use decision rules for hazmat installations based *FN*-curves (Jonkman, *et al.*, 2003).

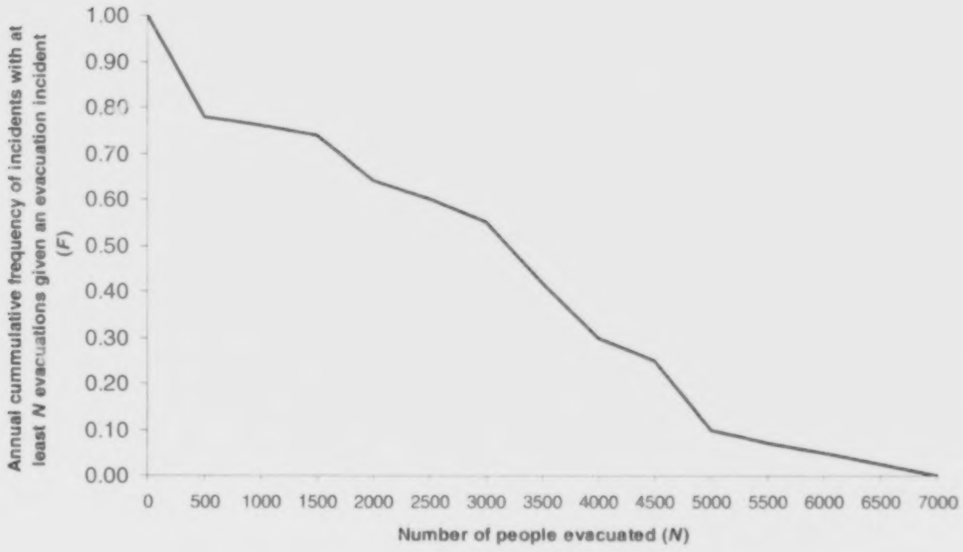


Figure 3.1. A conditional *FN*-curve (given an evacuation incident)

Clearly, more than one type of accident, release, incident, and consequence can occur during the hazmat transport activity. For example, a release of flammable liquid can lead to a variety of incidents such as a spill, a fire, or an explosion. To accommodate this, let $\mathcal{A}$, $\mathcal{M}$, $\mathcal{I}$, and $\mathcal{C}$ denote the set of possible accidents, releases, incidents, and consequences that may occur on road segment l. Suppose that all consequences (injuries and fatalities, property damage, and environmental damage) can be expressed in monetary terms (see Section 3.2.3). Then, the hazmat transport risk associated with road segment l can be expressed as

$$R_l := \sum_{a\in\mathcal{A}} \sum_{m\in\mathcal{M}} \sum_{i\in\mathcal{I}} \sum_{c\in\mathcal{C}} s_{lm} p_l(A_a, M_m, I_i, C_c) CONS_c \tag{3.4}$$

where, $CONS_c$ is the possible c-type consequence.

To summarize, we started with individual risk due to a single incident, then we moved on to risk due to multiple shipments, and on to societal risk, and finally to societal risk with multiple incidents.

However, in practice, researchers frequently neglect these conditional probabilities and simplify the analysis by considering the *expected loss* (or the *worst-case loss*) as the measure of risk. The expected value is calculated as the product of the probability of a release accident and the consequence of the incident (List *et al.*, 1991). Hence the hazmat transport risk associated with a road segment *l* can be expressed as

$$R_l := \sum_{m \in \mathcal{M}} s_{lm} p(M_m) c_{lm} \tag{3.5}$$

where, c_{lm} is the undesirable consequence due to the release of hazmat *m* on road segment *l*. This risk model is sometimes referred to as the *technical risk* (Erkut and Verter, 1998). The US DOT use this expected loss definition in their guidelines for transporting hazmats (US DOT, 1994). These simplifications are mainly due to the lack and inaccuracy of accident and exposure data.

As it is clear from the discussion above, QRA depends heavily on an estimation of probabilities. There are two primary means to estimate the accident, release, and incident probabilities: historical frequencies and logical diagrams (fault tree and event tree analysis).

Historical frequencies: We can use the number of hazmat transport accidents in a given time period and the total distance traveled by hazmat trucks in the same time period to calculate the accident rate on a unit road segment (i.e. accidents per km). The hazmat accident probability on road segment *l*, $p_l(A)$, can be obtained by multiplying the accident rate by the length of road segment *l*. To estimate $p_l(M_m|A)$, we need to calculate the percentage of hazmat accidents that result in a release of hazmat *m*. Similarly, we can use historical data to estimate $p_l(I|A, M_m)$ and $p_l(D|A, M_m, I)$. However, the occurrence of an accident may be influenced by intrinsic factors such as tunnels, rail bridges, road geometry, weather conditions, and human factors, as well as other factors correlated to traffic conditions, such as traffic volume and frequency of hazmat shipment. Consequently, some locations are more vulnerable to accidents than others. Therefore, a careful analysis should be done prior to the use of historical data.

The rarity of hazmat accidents may result in insufficient information to determine whether historical figures are relevant to the circumstances of concern, particularly regarding rare catastrophic accidents. Moreover, in estimating the associate probabilities on road segment l of a hazmat transportation route, the dependency to the impedances of preceding road segments should also be taken into account (Kara *et al.*, 2003 and Verter and Kara, 2001). We will discuss this dependency issue in more detail in Section 3.2.5.

Logical diagram-based techniques: An alternative way to estimate the frequency (and possibly consequences) of hazmat release incidents is the use of logical diagram-based techniques, namely fault tree and event tree analysis. *Fault Tree Analysis* (FTA) is a top-down analysis tool to identify the causes of events and to quantify various accident scenarios that would cause the system fail. It starts with an identified hazard (e.g., chlorine release due to a transport accident) as the root of a tree (or top event) and works backwards to determine its possible causes (e.g., collision accident, derailment, and relief valve poorly sealed) using two logical functions: OR and AND. The causative events are laid out in a tree with the branches connected by gates comprising one of these logical functions. The OR gate represents the union of events attached to the gate. An OR gate can have any number of inputs (branches). The event above the gate is realised if any one or more of the inputs occur. The AND gate represents the intersection of events attached to the gate. An AND gate can also have any number of inputs, but the event above the gate is only realised if all the inputs occur. Moreover, several fault trees can be combined into a single complex fault tree. FTA enables us to determine the probability of the top event on the basis of the probabilities of the basic events (e.g., $p(D|A,M,I)$ in (3.1), where death of an individual in hazmat transport accident is the top event) for which sufficient historical data exist or expert judgments are reliable.

Event Tree Analysis (ETA), on the other hand, is a bottom-up analysis tool. It takes at its starting point the event that can affect the system (e.g., an initial release of hazmat) and tracks them forward through sequences of interfacing system components to determine their possible consequences. It examines all possible responses to the initiating event, such as the functioning, failure, or partial failure of subsystems or different systems, in a tree structure with the branches developing from left to right. Each outcome of the branches is usually binary (i.e., the outcome occurs or does not occur). By assigning a probability to each branch, the probabilities of every possible outcome following the initiating event can be determined. ETA can be used in conjunction with FTA, called FETA, to identify and quantify the possible consequences of the top event in fault tree. Figure 3.2 shows a fault tree in conjunction with an event tree. For additional details and examples of fault and event tree construction, we refer to Henley and Kumamoto (1981), Vesely *et al.* (1981), and Rhyne (1994).

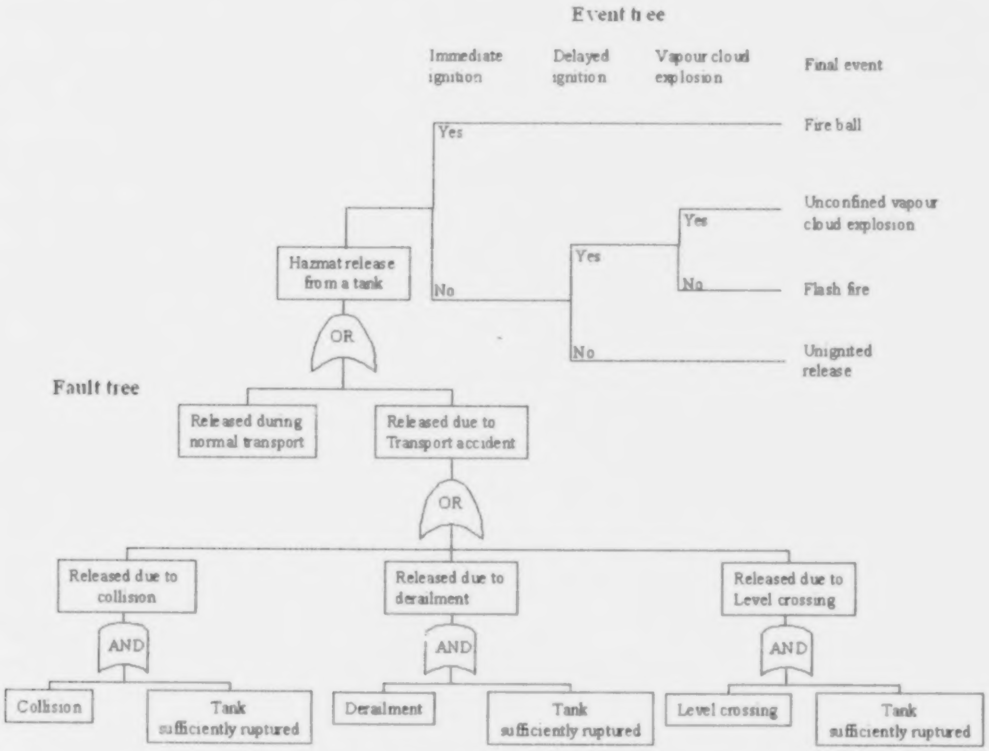

Event tree
Immediate ignition
Delayed ignition
Vapour cloud explosion
Final event
Yes
Fire ball
Yes
Unconfined vapour cloud explosion
Yes
No
Flash fire
No
No
Unignited release
Hazmat release from a tank
OR
Fault tree
Released during normal transport
Released due to Transport accident
OR
Released due to collision
Released due to derailment
Released due to Level crossing
AND
AND
AND
Collision
Tank sufficiently ruptured
Derailment
Tank sufficiently ruptured
Level crossing
Tank sufficiently ruptured

Figure 3.2. A fault tree in conjunction with an event tree for hazmat release (adapted from Alp, 1995)

Boykin *et al.* (1984) applied FETA to analyze the risks associate with the selection of technology alternatives in the chemical storage system. Pet-Armacost *et al.* (1999) used FETA in conjunction with two Monte Carlo simulations (one uses spreadsheet add-in @RISK and the other uses discrete event simulation software ARENA) to conduct a transportation risk analysis of Hydrazine in order to determine whether or not a relief valve should be used. FETA was used to decompose the transport process into its basic components and to identify the major sources of uncertainty. The event probabilities in the event trees were derived as functions of the parameters whose effects were not known. The impact of these parameters on the risks of toxic exposure, fire, and explosion was analyzed through Monte Carlo analysis and analysis of variance. Rosmuller and van Gelder (2003) used FETA to conduct a QRA for the hazmat transportation in the Netherlands. The results were used to formulate appropriate risk and rescue policies. They suggested that emergency response teams could use the release data for determining impact circles for road accidents and subsequently decide on detour routes. Moreover, expected distributions of release quantities could be used to facilitate the training of hazmat response personnel.

3.2 Consequence modelling and risk calculation

3.2.1. Modeling the impact area

There are many undesirable consequences of a hazmat transportation accident, such as economic losses, injuries, environmental pollution, damage to wildlife, and fatalities. These consequences are a function of the impact area (or exposure zone) and population, property, and environmental assets within the impact area. The shape and size of an impact area depends not only on the substance being transported but also on other factors, such as topology, weather, and wind speed and direction. Estimating, a priori, the impact area of a potential accident is difficult. Researchers used different geometric shapes to model the impact area such as a band of fixed width around each route segment (e.g., Batta and Chiu, 1988 and ReVelle *et al.*, 1991), a circle (called danger circle), with a substance-dependent radius centered at the incident location (e.g., Erkut and Verter, 1998 and Kara *et al.*, 2003), rectangle around the route segment (e.g., ALK Associates, 1994), and an ellipse shape based on the Gaussian plume model (e.g., Patel and Horowitz, 1990, Chakraborty and Armstrong, 1995, and Zhang *et al.*, 2000). Figure 3.3 shows these four shapes of the impact area that have been used in the literature.

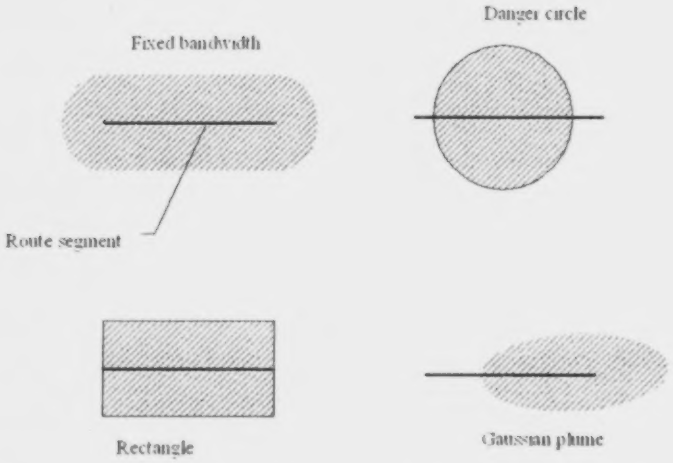


Figure 3.3. Possible shapes of impact area around the route segment

Perhaps the most common approximation of the impact zone is the *danger circle*. By moving the danger circle along a route segment between two nodes (see Kara *et al.*, 2003), we get the fixed-bandwidth approximation and by cutting off the circular segments at the two ends we get the rectangle approximation. The bandwidth or radius is substance-dependent but it is assumed to be constant for a given shipment, which means that this approximation does not consider effect of the distance on the level of impact. One can determine the radius by considering the *evacuation distance* (i.e., the *initial isolation zone*) when a hazmat incident occurs, for example 0.8 km for flammable hazmats and 1.6 km for flammable and explosive hazmats (CANUTEC, 2004). The central assumption in these models is that each individual within the danger zone will be impacted equally and no one outside of this area will be impacted.

The modeling of an impact area can also be considered from the point of view of the affected population center. For example, a population center is commonly modeled as a point on the plane, where all inhabitants of the population center are considered to experience the same impact from a hazmat incident on a road segment nearby. The impact on this aggregation point depends on the distance between the point and the incident location. For example, the impact can be inversely proportional to the square of the Euclidean distance between the two points. However, a GIS enables researchers to represent the spatial distribution of population density more accurately (see, for example, Figure 3.5) rather than using aggregation points. Erkut and Verter (1995b) proposed a model of the spatial distribution of population by using a polygon. Verter and Kara (2001) incorporated this in a GIS, and developed a large-scale risk assessment model for the provinces of Ontario and Quebec.

3.2.2 Gaussian plume model

In an airborne hazmat (e.g., chlorine, propane and ammonia) accident, the concentration of the airborne contaminant varies with distance from the source of accident. It will be lower as the gas disperses with distance and wind. Therefore, the three approaches discussed above can result in poor approximations of the impact area. In this case, researchers have usually resorted to the Gaussian plume model (GPM) (Hanna *et al.*, 1993, Patel and Horowitz, 1994, Chang *et al.*, 1997, Zhang *et al.*, 2000, and Puliafito *et al.*, 2003). The Gaussian plume model is based on several limiting assumptions: (1) the gas does not change its chemical properties during dispersion; (2) the terrain is unobstructed and flat; (3) the ground surface does not absorb the gas; (4) the wind speed and direction is stable during the dispersion period; and (5) the emission rate is constant. These assumptions certainly limit the application of GPM, for example assumption (1) restricts the applicability of the GPM to stable chemicals and to accidents which do not result in an explosion (Zhang *et al.*, 2000). The GPM is formulated as

$$C(x,y,z,h_e)=\frac{Q}{2\pi\mu\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right)\left[\exp\left(-\frac{1}{2}\left(\frac{z-h_e}{\sigma_z}\right)^2\right)+\exp\left(-\frac{1}{2}\left(\frac{z+h_e}{\sigma_z}\right)^2\right)\right],$$

where, C is the concentration level (mass per unit volume - $\mu g/m^3$ or parts per million – ppm), x the distance downwind from the source (m), y the distance crosswind (perpendicular) from the source (m), z the elevation of the destination point (m), h_e the elevation of the source (m), Q the release rate of pollutant (mass emission rate - g/s or volumetric volume rate - m^3/s), μ the average wind speed (m/s), σ_y and σ_z the dispersion parameters in the y and z directions (m).

In hazmat dispersion from traffic accidents, it is usually assumed that the source is on the ground (i.e., $h_e = 0$) and we are interested in the ground concentration level (i.e., $z = 0$). Therefore, we obtain

$$C(x, y, z, h_e) = C(x, y) = \frac{Q}{\pi \mu \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right)$$

Figure 3.4 shows bell-shaped curves of concentration levels $C(x, y)$ for two different downwind distances: (a) the concentration of the pollutant is high at the source of the spill ($x = 0$) and the Gaussian distribution has a pronounced peak; (b) as the pollutant drifts farther downwind ($x >> 0$), it spreads out and the bell-shape becomes wider and flatter.

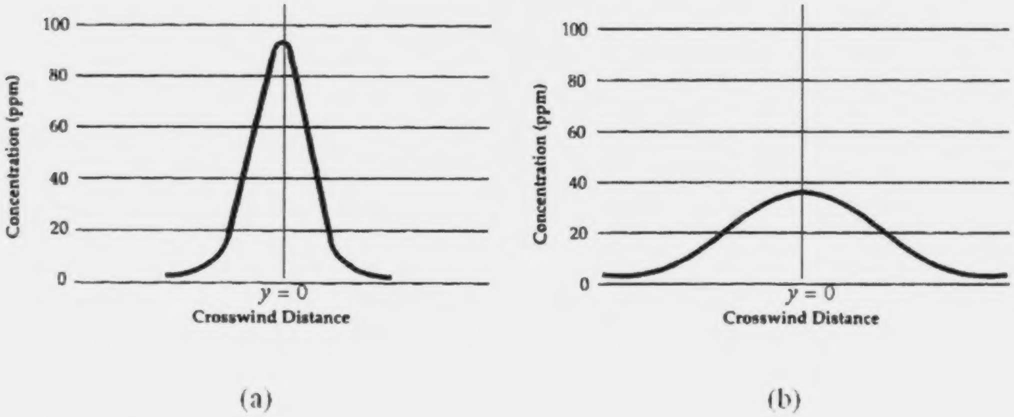


Figure 3.4. The bell-shape of concentration level $C(x, y)$: (a) Gaussian distribution at $x = 0$ and (b) Gaussian distribution at $x >> 0$ (Chakraborty and Armstrong, 1995)

The release rate, Q, depends on container volume, hazmat type, and rupture diameter. To calculate Q, one can use ALOHA (see Section 2.5). ALOHA can also be used for estimating the concentration level, $C(x, y)$, but its results are only reliable within one hour of the release event, and 10 kilometers from the release source. The dispersion parameters, σ_y and σ_z, can be determined as a function of downwind distance x (Pasquill and Smith, 1983 and Arya, 1999).

The individual risk, that is the probability that an individual at location j with coordinate (j^x, j^y) will experience an undesirable consequence (such as evacuation, or injury, or death) as a result of a release at i, p_{ij}, can be represented as a function of the concentration of airborne contaminant at j, $C_{ij} := C(|j^x - i^x|, |j^y - i^y|)$. The American Institute of Chemical Engineers (2000) suggests a *probit function* to model $p_{ij}(C_{ij})$. Consequently, the social risk can be obtained by multiplying $p_{ij}(C_{ij})$ with the population size at location j.

A simpler alternative way to estimate the consequence of airborne hazmat accident is to use the standard concentration level to determine the threshold distances for different consequences (e.g., fatalities and injuries), such as Immediately Dangerous to Life and Health (IDLH) (NIOSH, 1994) developed by the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA). The IDLH-values represent the maximum concentration from which one could escape without injury or irreversible health effects (e.g., severe eye or respiratory irritation, disorientation, or lack of coordination) within 30 minutes of exposure. For example, the IDLH-values for carbon dioxide and propane are 40,000 ppm and 2,100 ppm respectively. These numbers hold for enclosed spaces (and not open-air). To be used in an open environment, for example, Verma and Verter (2005) considered a propane dispersion of 2,100 ppm per second and assumed that roughly a 4-5 minute propane exposure at this IDLH level can cause minor injury while a 30-35 minute exposure can cause major injury or fatality. Using these assumptions, they defined a fatality zone (if the concentration level $C \geq 4{,}200{,}000$), an injury zone (if $600{,}000 \leq C < 4{,}200{,}000$) and a non-exposure zone (if $C < 600{,}000$) where C is given in ppm. Hence, the threshold distance is determined by the level curve of the associated hazmat IDLH-value and the associated consequence can be represented as the function of the population size within the level curve. Figure 3.5 shows the population densities within different concentration levels of a single source release.

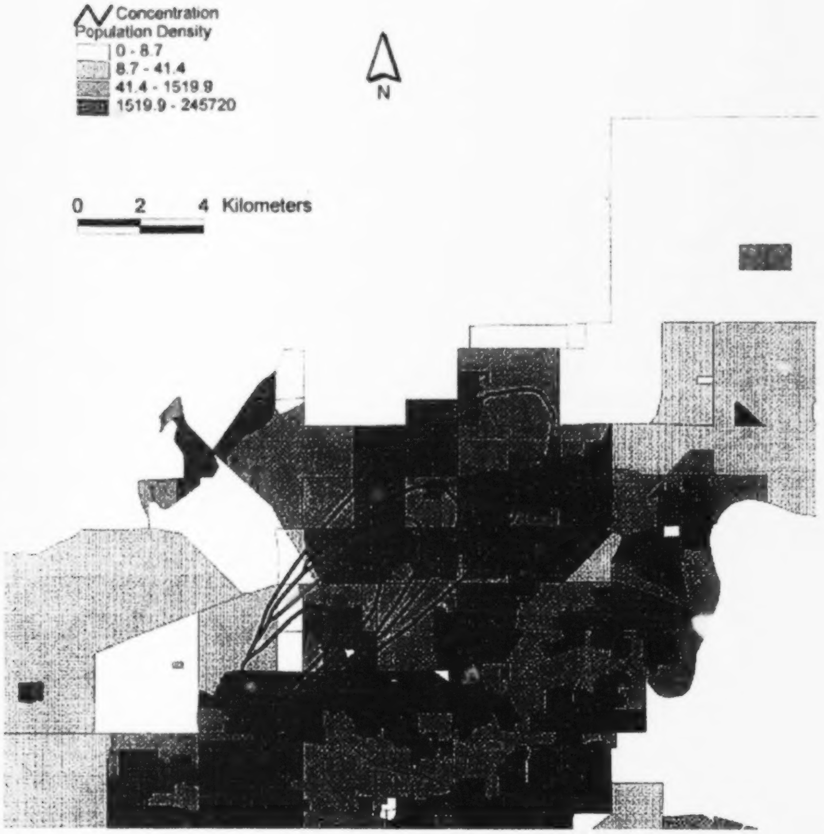
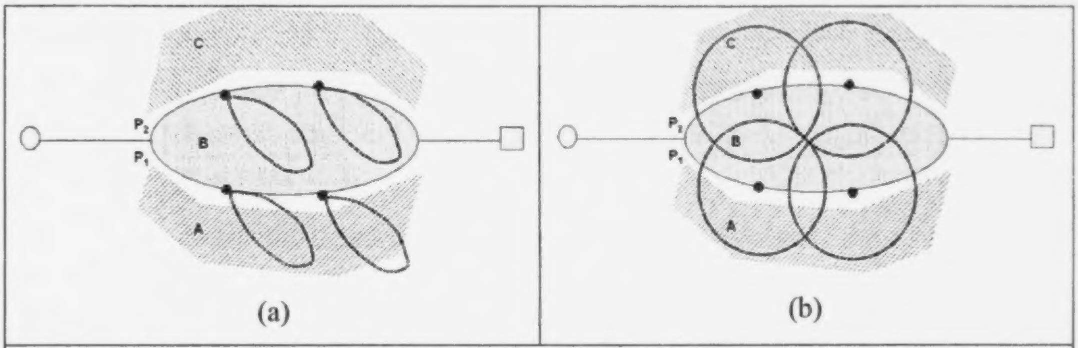


Figure 3.5. Population densities within different concentration levels (Zhang *et al.* , 2000)

The following conceptual example demonstrates how an improper assessment of the impact area may lead to a high-risk routing decision. Consider two East-West routes around a city that may be used for propane shipments: South (P_S) and North (P_N) routes (see Figure 3.6a). Assume each route segment in both routes has the same incident probability. Suppose these routes divide the city into three regions *A*, *B*, *C*, where each region has uniform population density. Among these regions, suppose that region *B* is the most densely populated one and region *C* is the least densely populated one. Moreover, suppose that the prevalent wind direction is South-East. Figure 3.6b shows concentration contours of route segments in P_S and P_N, according to the IDLH value. Since the population density in the impact area of route P_S is less than that of P_N, one might send propane via route P_S . In contrast, if one were to use a danger circle instead of the Gaussian plume model, neglecting the type of hazmat and the wind direction, one may select route P_N instead of P_S. This decision would expose more people in case of an incident as propane would drift south-eastwardly into region *B*. As this simple example demonstrates a careful analysis is necessary prior to defining the impact area.



(a)

(b)

Figure 3.6. (a) Gaussian plume model vs (b) Danger circle

3.2.3 Risk cost

To estimate the cost of a hazmat release incident, various consequences must be considered. The consequences can be categorized into (Abkowitz *et al.*, 2001 and FMSCA, 2001): injuries and fatalities (or often referred to as *population exposure*), cleanup costs, property damage, evacuation, product loss, traffic incident delay, and environmental damage. All impacts must be converted to the same unit (for example dollars) to permit comparison and complication of the total impact cost. The discussion of risk costs presented here deals primarily with hazmat incidents on highways.

Injuries and fatalities

Finding a dollar value of human life and safety is perhaps the most difficult and controversial issue. Some find it offensive; others argue that any dollar value assigned to human life would be too low. Yet it is possible to estimate the value indirectly. Insurance payments offer a simple estimate. Perhaps more relevant is the figure used by government agencies to prioritize their projects that reduce fatalities and injuries. Clearly if an agency is making a choice between Project A which will save X lives and cost P dollars per year and Project B which will save Y lives and cost Q dollar per year, they are implicitly using a trade-off value that converts fatalities to dollars—regardless of whether or not the trade-off is made explicit.

The value of an injury or fatality in a hazmat incident can be estimated from different perspectives (FMCSA, 2001). For example, one can value an injury or fatality in terms of lost income and economic productivity to society. The National Highway Transportation Safety Administration (NHTSA) estimates the cost of fatalities and injuries by considering both direct and indirect costs to individuals and to society (NHTSA, 1996). Direct costs include emergency treatment, initial medical costs, rehabilitation costs, long-term care and treatment, insurance administrative expenses, legal costs, and employer/workplace costs. Indirect costs are productivity losses in the workplace due to temporary and permanent disability and decreases in productivity at home resulting from these disabilities. In 1996 dollars, a fatality costs about $913,000 and a critical injury costs about $780,000.

In addition to the economic cost components discussed above, The National Safety Council (NSC) also includes the value of a person's natural desire to live longer or to protect the quality of one's life (NSC, 2003). This value indicates what people are willing to pay to reduce their safety and health risks. Hence, the cost estimates include wage and productivity losses, such as wages and fringe benefits, replacement cost and travel delays caused by the accident; medical expenses, such as doctor fees, hospital charges, cost of medication, future medical costs and other emergency medical services; administrative expenses, such as insurance premiums and paid claims, police and legal costs; motor vehicle damage, such as property damage to vehicles; and employer costs, such as time lost by uninjured workers, investigation and reporting time, production slowdowns, training of replacement workers and extra costs of overtime for uninsured workers (FMCSA, 2001). The 2003 estimates of incapacitating injury and fatality costs are $181,000 and $3,610,000, respectively.

Finally, US DOT values injuries and deaths at the amount they would spend to avoid an injury or fatality (FMCSA, 2001). This averages out to be $400,000 to avoid an injury requiring hospitalization and $2,800,000 to avoid a fatality.

Cleanup costs

Cleanup costs are assumed to encompass the costs of both stopping the spread of a spill and removing spilled materials (Abkowitz *et al.*, 2001 and FMCSA, 2001). Such costs vary widely depending on the size, type of materials, and location of the spill. Some national database systems, such as the Hazardous Materials Information System (HMIS) of US DOT and The Workplace Hazardous Materials Information System (WHMIS) of Health Canada, can be used as references for the cleanup costs. For the period 1990-1999, cleanup costs averaged about $24,000 per en-route accident, $1,300 per cleanup for an en-route incident spill, and $260 for an unloading/loading accident and incident spill cleanup (HMIS database).

Property damage

Property damage encompasses damage to other vehicles, which may have been involved in the incident, as well as damage to both public and private property (e.g., private buildings, public utilities, public roadways). For example, from HMIS database of the period 1990-1999, the average property damage for flammable and combustible liquids en route accidents was $16,041, while the average property damage for en-route incident spills was $274. Average property damage for leaks occurring during loading and unloading incidents and accidents was $68. Average property damage for flammable gases en route accidents, en route spills, and loading/unloading incidents were $3,147, $173, and $2,315, respectively. For corrosive materials, the average values for en route accidents, en route spill incidents, and loading/unloading incidents were $3,104, $67, and $17, respectively (FMCSA, 2001).

Evacuation

There are numerous variables which complicate the estimation of the cost of evacuation. These include the expense for temporary lodging and food, losses due to lost wages and business disruptions, inconvenience to the public and the cost of agencies assisting in evacuation. A reasonable estimate would be $1,000 per person evacuated (TRB, 1993). This $1,000 estimate is also used by the Federal Railroad Administration (FRA) to estimate impacts from railroad evacuations.

Product loss

Product loss refers to the quantity and value of the hazmats lost during a spill. For example, from the HMIS database for period 1990 – 1999, the average cost of product lost of flammable and combustible liquids en route accident related spills was $3,208 per spill. Similarly, for flammable gases accidents, the average cost of product lost per en-route accident related spill was $1,140 per spill. Corrosive material spill accidents averaged $4,910 per spill in product loss.

Traffic incident delay

Hazmat spills typically require an emergency response that causes a significant traffic delay. This type of traffic delay is called incident delay. If traffic volume and incident situation (e.g., the traffic arrival rate, road capacity reduction, and incident duration) is known, a deterministic model can be used to estimate the incident delay. For example, Morales (1989) used a deterministic queueing model and Wirasinghe (1978) and Al-Deek *et al.* (1995) used models based on shock-wave theory. Due to its simplicity, the Morales model is often used by practitioners (see for example Abkowitz *et al.*, 2001, and FMCSA, 2001). However, these deterministic models are inappropriate for prediction of incident delay in real-time situation where the incident duration is unknown. In this case, incident delay is best modeled by a random variable that represents the stochastic characteristics associated with the incident (as in Fu and Rilett, 1997).

To obtain the associated costs of incident delays, information on the occurrence of an incident or the split between trucks and other vehicles on the various highway systems are required. Earlier studies (Grenzeback *et al.*, 1990) assumed the hourly cost of incident delay to be about $20 for trucks and $10 for other vehicles, which accounts for the value of a driver's time and fuel consumption costs. The total cost traffic incident delay is then obtained by multiplying this dollar value of incident delay with the total number of person-hours of delay given by the model discussed above.

Environmental damage

Environmental damage consists of damage to the environment that remains after the cleanup. This damage can be calculated in terms of loss of economic productivity, such as agricultural production lost and/or in loss of habitat or ecosystem deterioration (FMSCA, 2001). The loss of agricultural productivity can be estimated, for example using the quantity of crops that are not grown during a 20-year period due to contamination. Using wheat as an example, a contaminated field that can produce 35 bushels per acre/year would result in an (undiscounted) gross income loss of $3,500/acre over a 20-year period assuming a fixed value of $5/bushel. To calculate the natural resource environmental damage from a hazmat incident is more complicated. We need to know how much material was spilled, where the spill occurred, and what sort of surface it covered. Using, for example, HMIS data, one can estimate the dollar cost of this damage.

As the discussion in this section points out, while there are different types of costs associated with a hazmat transport incident, in most cases all other costs are dwarfed by the cost of fatalities and injuries and the cost of evacuations in cases of major spills. Perhaps this is a reason why many OR analysts focus exclusively on populations inside a danger circle.

3.2.4 Perceived risks

All consequences we discussed so far assume that society is risk-neutral; i.e. we are indifferent between two consequence distributions, as long as their expected values are equal. For example, risk neutrality assumes that a single incident causing 100 fatalities is equivalent (or equally undesirable to the society) to 100 incidents causing one fatality each, since in both cases the total number of fatalities is the same. However, most individuals would judge a low probability/high consequence (LPHC) event as more undesirable than a high probability/low consequence (HPLC) event even if the expected consequences of the two events are equal (Erkut and Verter, 1998). Consequently when dealing with LPHC events, most human decision makers tend to exhibit risk aversion; a single incident causing 100 fatalities is perceived as much more undesirable than 100 incidents each causing a single fatality.

A simple way to incorporate risk attitude to risk models is to add a risk preference (or tolerance) factor α as an exponent to the consequence values. For example, if the risk assessment deals with the population exposure, then the societal risk on road segment l (see (3.2), droppingthe hazmat index m) can be expressed as (see, e.g. Slovic *et al.*, 1984 and Abkowitz *et al.*, 1992)

$$R_l := s_l \iint_L p_l(D_{xy}|A,M,I)\,p_l(I|A,M)\,p_l(M|A)\,p_l(A)(POP_l(x,y))^{\alpha}\,dx\,dy$$

By considering only one shipment (or one trip) and one type of hazmat spill, the traditional expected loss model of risk (3.5) can thus be modified as (see e.g., Slovic *et al.*, 1984, Abkowitz *et al.*, 1992 Erkut and Verter, 1998, and Erkut and Ingolfsson, 2000):

$$R_l := p_l(POP_l)^{\alpha}$$

Figure 3.7 shows three different values of α associated with three different risk preferences: $\alpha = 1$ models risk neutrality; $\alpha > 1$ models risk aversion; and $\alpha < 1$ models risk-taking behavior. The greater the value of α, the higher the aversion to the risk of a hazmat incident. The risk-aversion model assumes that the $(i+1)^{st}$ life lost is more costly than the i^{th} life lost, for all possible values of i. Of course as α is increased, any route selection model that operates with an objective of minimizing total risk is eventually reduced to a model that minimizes the maximum risk, as shown by the following small example. Consider a hazmat shipment from an origin O to a destination D. There are two routes (North and South) between O and D, P_1 and P_2, each consisting of two route segments. Suppose that the incident probability and the population density in the impact area of the two segments of route P_1 are $(10^{-4};25)$ and $(10^{-4};75)$, and those of P_2 are $(10^{-5};100)$ and $(10^{-5};400)$. The total risks associated with P_1 and P_2 are 10^{-2} and 5×10^{-3}, respectively, and the maximum risks are 75×10^{-4} and 4×10^{-3}, respectively. For $\alpha = 1$, we select P_2, the route with lower total risk. As α approaches infinity, the problem turns into one of minimizing the maximum risk, and we select P_1. Figure 3.8

shows how the optimal routing decision changes from P_2 to P_1 as the risk-aversion factor α increases.

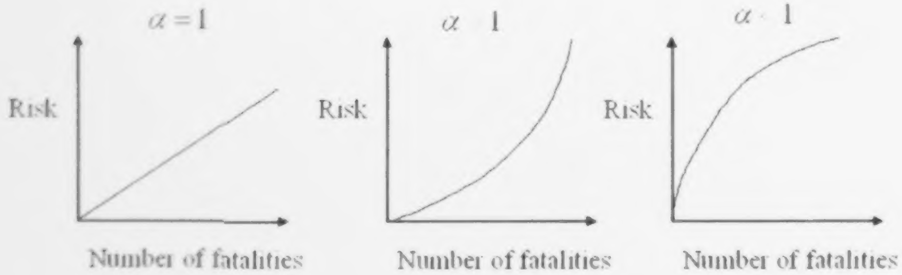


Figure 3.7. Three different risk preferences: $\alpha = 1$ risk neutral; $\alpha > 1$ risk aversion; $\alpha < 1$ risk proneness

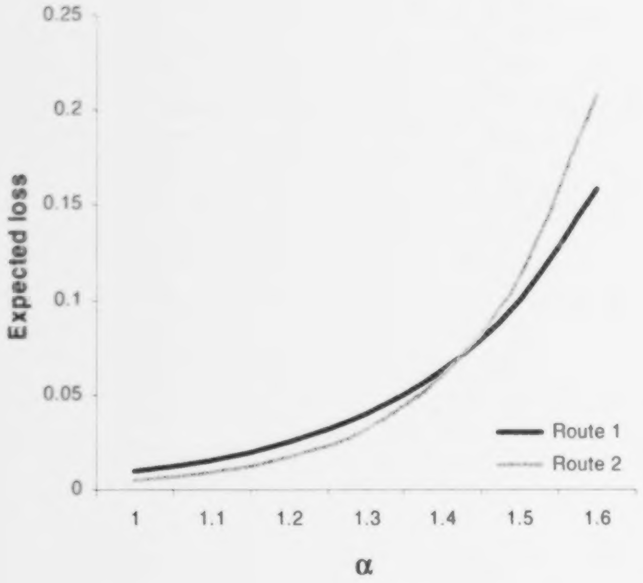


Figure 3.8. Routing decision for different values of α, based on perceived risk

The perceived risk model can be thought of as a simple (dis)utility model. It is possible to model risk disutility in other ways. For example, Kalelkar and Brinks (1978) proposed an empirical disutility function that was constructed by using a series of questions posed to decision makers. Erkut and Ingolfsson (2000) proposed an exponential disutility function to model risk aversion.

3.3 Risk on a hazmat transportation route

Up to this point, we discussed hazmat transport risk in general. Now we discuss the modeling of risk along an edge, and then along a route, of a transport network. In other words, we now move from point risk (risk due to accident at a given point) to linear risk (risk along an edge and route). Consider a road network $G=(N,E)$ with node set N and edge set E. The nodes correspond to the origin, the destination, road intersections, and population centers and the edges correspond to road segments connecting two nodes. (We note that one does not have to model population centres as nodes if one uses a GIS as discussed earlier.) We first focus our discussion on road transportation, and then move to hazmat transportation on rail.

Note that in the context of hazmat routing it is desirable that each point on an edge has the same incident probability and level of consequence (e.g., population density). Therefore, a long stretch of a highway that goes through a series of population centers and farmland should not be represented as a single edge, but as a series of edges. Thus, a network to be used for hazmat routing is usually different from a network to be used for other transport planning purposes. This difference is quite important since it limits the portability of network databases between different transport applications (Erkut and Verter, 1998). We first discuss the modeling of risk along an edge.

3.3.1 Edge risk

Erkut and Verter (1998) proposed a risk model that takes into account the dependency to the impedances of preceding road segments. Suppose that an edge is a collection of n unit road segments each with the same incident probability p and consequence c. The probability p is obtained from (3.1) and the consequence c is determined by taking a proper impact area of a unit road segment. If, for example the impact area of a unit road segment is modeled as a danger circle, then the impact area of an edge is a semicircular shape with the same radius as the danger circle, as shown in Figure 3.9. The vehicle will either have an incident on the first road segment, or it will make it safely to the second segment. If it makes it safely to the second segment, it will either have an incident in the second segment, or it will not, and so on. They assumed that the trip ends if an incident occurs. Hence, the expected risk associated with this edge would be

$$pc + (1-p)pc + (1-p)^2 pc + \cdots + (1-p)^{n-1} pc \tag{3.6}$$

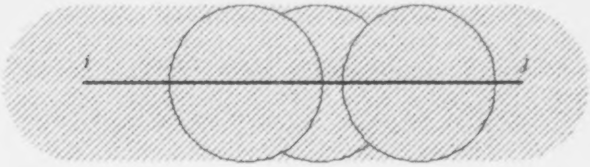


Figure 3.9. Semicircular impact area around link (i, j)

Since the incident probability p is at most on the order of 10^{-6} per trip per kilometre (based on North American data, Harwood *et al.*, 1993), we can approximate

$$p^s \cong 0, \text{ for } s > 1 \tag{3.7}$$

Consequently, the risk of hazmat transport on this edge becomes pnc. For edge i, we can thus define the risk as

$$r_i = p_i c_i \tag{3.8}$$

where the probability of an incident on edge i, is $p_i := np$, and the associated consequence is $c_i := c$.

Note that this simple risk model works under an assumption of uniform incident probability and uniform consequence along an edge. If these two attributes are not uniform, the risk computation on either an edge or an origin-destination route will be more complicated. In practice, however, this assumption will be valid if we define long stretches of a highway as a series of edges. (In other words, it is not only the network topology, but also the value of the edge attributes that define an edge. The edges must be short enough that the accident probability and the consequence are constant along the entire edge.) This edge risk definition can be considered as a generalization of the classical (or traditional) risk definition, which considers risk as an expected loss (see

Section 3.1). The expected loss can be obtained from (3.6) by defining $n = 1$, i.e., each unit road segment is considered as an edge of the road network.

3.3.2 Path risk

An origin-destination route P for a hazmat shipment is a collection of edges, where travel on this path can be viewed as a probabilistic experiment as shown in Figure 3.10 (Erkut and Verter, 1998). Similar to the argument used above, a hazmat vehicle will travel along the i^{th} edge of P only if there is no incident on the first $(i-1)$ edges of P (i.e., an incident terminates a trip along P). Suppose that the path P has n edges. Note that n may represents the length of the path if each edge $e_i \in E$, $i = 1, \cdots, n$ has length of one unit. The expected path risk associated with this trip can be expressed as

$$R(P) = \sum_{i=1}^{n} \prod_{j=1}^{i-1} (1 - p_j) p_i c_i \tag{3.9}$$

where $(1-p_1)(1-p_2)\cdots(1-p_{i-1})p_i c_i$ is the impedance of the i^{th} edge of P. By this definition, edge impedances are path-dependent.

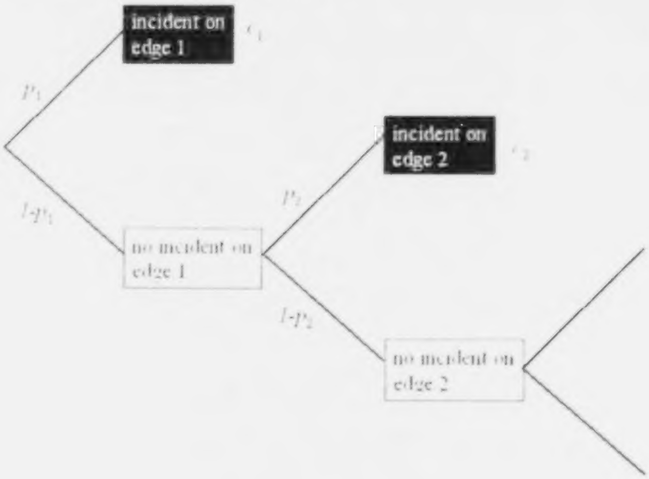


Figure 3.10. Partial probability path displaying possible outcomes of a hazmat transport along a path, where p_i is the incident probability and c_i is the associated consequence along the ith edge of the path (Erkut and Verter, 1998)

Using an approximation similar to (3.7), that is assuming

$$p_i p_j \cong 0 \text{ for all edges } i, j, \tag{3.10}$$

Section 3.1). The expected loss can be obtained from (3.6) by defining $n = 1$, i.e., each unit road segment is considered as an edge of the road network.

3.3.2 Path risk

An origin-destination route *P* for a hazmat shipment is a collection of edges, where travel on this path can be viewed as a probabilistic experiment as shown in Figure 3.10 (Erkut and Verter, 1998). Similar to the argument used above, a hazmat vehicle will travel along the i^{th} edge of *P* only if there is no incident on the first $(i-1)$ edges of *P* (i.e., an incident terminates a trip along *P*). Suppose that the path *P* has *n* edges. Note that *n* may represents the length of the path if each edge $e_i \in E$, $i = 1, \cdots, n$ has length of one unit. The expected path risk associated with this trip can be expressed as

$$R(P) = \sum_{i=1}^{n} \prod_{j=1}^{i-1} (1 - p_j) p_i c_i \tag{3.9}$$

where $(1-p_1)(1-p_2)\cdots(1-p_{i-1})p_i c_i$ is the impedance of the i^{th} edge of *P*. By this definition, edge impedances are path-dependent.

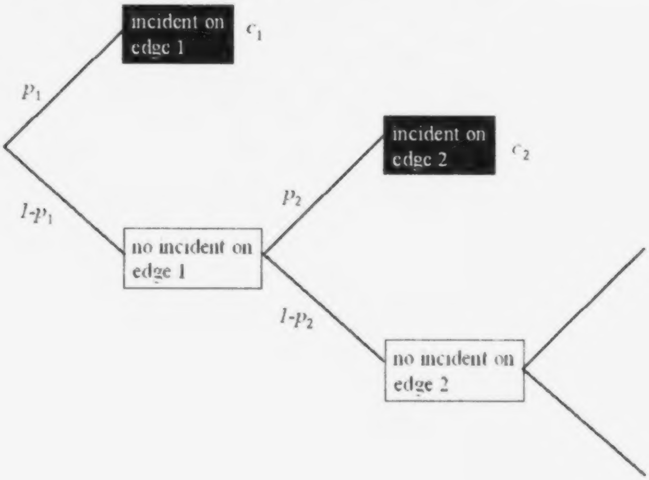


Figure 3.10. Partial probability path displaying possible outcomes of a hazmat transport along a path, where p_i is the incident probability and c_i is the associated consequence along the i^{th} edge of the path (Erkut and Verter, 1998)

Using an approximation similar to (3.7), that is assuming

$$p_i p_j \cong 0 \text{ for all edges } i, j, \tag{3.10}$$

we obtain a very simple linear form of path risk:

$$R'(P)=\sum_{i=1}^{n} p_i c_i \tag{3.11}$$

This model is often referred to as the traditional risk model, since it explicitly uses the expected consequence definition of risk. Note that this model is simple to explain and justify, and it is not data intensive; it requires only one accident probability and one consequence figure per edge. Furthermore, it is rather easy to work with in optimization models. In fact, minimizing (3.11) for a given OD pair in a hazmat transport network is a shortest path problem which is solved easily for even large networks. For these reasons, most papers on hazmat transportation use this traditional risk model (Erkut and Verter, 1998). The US DOT also uses this approach in their guidelines (US DOT, 1994).

This simple risk model makes a tacit assumption that the hazmat vehicle will travel along every edge on the path, regardless of what happened on earlier edges. Consequently, a single hazmat trip can result in several incidents (with a very small probability). In some cases, though very unlikely, this assumption is practically reasonable. After a minor incident, the cargo may still be transported to the destination, perhaps on a different vehicle and/or on different route. Nevertheless, since incident rates for hazardous materials are very low, the probability of the conditioning event that an incident has not yet occurred when an edge *i* is reached will always be very close to 1. Therefore, the two assumptions (an incident terminates a trip and an incident does not terminate a trip) and (3.9) and (3.11), consequently, will differ insignificantly. Erkut and Verter (1998) point out that this approximation is likely to result in a very small error (less than 0.25% in most cases) in measuring the incidence probability along a hazmat transport route. Erkut and Ingolfsson (2000) provide an upper bound of $\exp(np_{\max})-1$ on the percent of error introduced by (3.11) relative to (3.9), where $p_{\max}$ is an upper bound on the incident probability on any edge. Formally

$$\frac{R'(P)-R(P)}{R(P)}<\exp(np_{\max})-1$$

For example, for a path *P* with length 4,800 km, using an incident probability of 10^{-6} per trip-km, we can compute an upper bound of $\exp(np_{\max})-1=\exp(0.004800)-1$, which is

0.48%. This upper bound is obtained by assuming that accidents along any edge *i* with length l_i occur according to a spatial Poisson process with rate λ_i per distance unit. Under this assumption, the risk on path *P* can be obtained as

$$R^e(P) = \sum_{i=1}^{n} \prod_{j=1}^{i-1} \exp(-p_j)(1-\exp(-p_i))c_i \tag{3.12}$$

where $p_i = \lambda_i l_i$. By defining

$$q_i := 1-\exp(-p_i) \tag{3.13}$$

for all edges *i*, (3.12) reduces to (3.9) with q_i replacing p_i.

Although the traditional risk model has been the most popular one, many other hazmat transport risk models have been proposed in the literature. Table 3.1 summarizes nine models and cites studies that have used each model. Each of the seven models that use probabilities are based on approximation (3.10), even though this approximation is usually not mentioned explicitly. We will refer to the alternate expressions of these seven models without using approximation (3.10) as "exact." Most of the models use population exposure as the consequence measure. In the population exposure model, c_i denotes the total population in the rectangle shape impact area that stretches along edge *i*. Other models use the circle-shaped impact area. Based on the empirical analysis on the U.S. road network, Erkut and Verter (1998) suggest that the choice of risk model is important because it effects the path selection decision and the optimal path for a certain criterion can perform very poorly under another. Therefore, researchers as well as practitioners must pay considerable attention to the risk modeling in hazmat transport.

Table 3.1. Alternative models of path risk (adapted from Erkut and Ingolfsson, 2005)

Model	Approximation approach	Satisfy Axioms? (approximation/ exact model) Y=Yes; N=No ; NA = Not Applicable			Sample references
		Axiom 1	Axiom 2	Axiom 3	

Traditional risk	$\sum_{i=1}^{n} p_i c_i$	Y/N	Y/N	Y/N	US DOT, 1994; Alp, 1995; Zhang *et al.*, 2000
Population exposure	$\sum_{i=1}^{n} c_i$	NA/Y	NA/Y	NA/Y	Batta and Chiu, 1988; ReVelle *et al.*, 1991
Incident probability	$\sum_{i=1}^{n} p_i$	Y/Y	Y/Y	Y/Y	Saccomanno and Chan 1985; Abkowitz *et al.*, 1992
Perceived risk	$\sum_{i=1}^{n} p_i c_i^{\alpha}$, $\alpha > 0$	Y/N	Y/N	Y/N	Abkowitz *et al.*, 1992
Conditional risk	$\sum_{i=1}^{n} p_i c_i \Big/ \sum_{i=1}^{n} p_i$	N/N	N/N	N/N	Sivakumar *et al.*, 1993, 1995; Sherali *et al.*, 1997
Maximum population exposure	$\operatorname{Max}_{e_i \in P} c_i$	NA/Y	NA/Y	NA/Y	Erkut and Ingolfsson, 2000
Expected disutility	$\sum_{i=1}^{n} p_i(\exp(\alpha c_i) - 1)$, $\alpha > 0$	Y/N	Y/N	Y/N	Erkut and Ingolfsson, 2000
Mean-Variance	$\sum_{i=1}^{n} \left(p_i c_i + k p_i c_i^2\right)$, $k > 0$	Y/N	Y/N	Y/N	Erkut and Ingolfsson, 2000
Demand satisfaction	$\sum_{i=1}^{n} (1 - \exp(-p_i)) c_i \prod_{j=i}^{n} \exp(p_j)$	NA/Y	NA/N	NA/Y	Erkut and Ingolfsson, 2005

Note: The three axioms tabulated here are discussed in the next subsection

We now discuss briefly the last three models in Table 3.1. These are the most complicated (and most recent) hazmat transport risk models.

Expected disutility model

The disutility model incorporates the risk aversion of the society towards hazmat incidents, especially the catastrophic incidents (incidents with very large consequences). Erkut and Ingolfsson (2000) assumed that hazmat incidents occur according to a spatial, non-homogeneous Poisson process defined over the edges of the network. Let N_i and X_i denote the number of hazmat incidents that occur on the i^{th}-edge and the number of people affected by a hazmat incident on the i^{th}-edge, respectively, of path *P*, where N_i has a Possion distribution with a parameter p_i, the incident probability on i^{th}-edge of path *P*. We can thus define $X_i = c_i N_i$, where c_i denotes the associate population exposure. The disutility function is defined as $u(X) := \exp(\alpha X)$, where the constant $\alpha > 0$ is a measure of catastrophe aversion. The higher the values of α, the more extreme the catastrophe aversion. By assuming that a single trip can result in several incidents, the expected disutility for a path *P* can be obtained as $E(u(X)) = \exp\left[\sum_{i=1}^{n} p_i(\exp(\alpha c_i) - 1)\right]$. Minimizing $E(u(X))$ is then equivalent to minimizing the summation in the exponent, i.e., $\sum_{i=1}^{n} p_i(\exp(\alpha c_i) - 1)$. Hence, finding a minimum disutility path is equivalent to finding a shortest path with edge attribute $p_i(\exp(\alpha c_i) - 1)$. The magnitude of the edge attributes can become very large. For example, suppose the population exposure is 10,000, the incident probability is 10^{-6}, and the risk aversion constant is 0.01. Then, the edge attribute is $10^{-6}(\exp(100) - 1) \approx 10^{36}$. As the risk aversion constant α increases, the edge attribute will approach infinity. Consequently, this will ban the associated edge from consideration during a route selection process that seeks a finite solution. Under an assumption that an incident terminates the trip, the expected utility for a path *P* (i.e., the exact model) can be obtained as

$$E(u(X)) = \exp\left[\sum_{i=1}^{n} r_i(\exp(\alpha c_i) - 1)\right]$$

where

$$r_i := \prod_{j=1}^{i-1} \exp(-p_j)[1 - \exp(-p_i)],\ e_i \in P \tag{3.14}$$

denotes the incident probability on edge *i* conditioned that no incident occurred on the first $(i - 1)$ edges. By definition, r_i are path dependent.

Mean-variance model

Many available risk models are based solely on the expected value of the risk and ignore how risk may deviate from the mean value. Under the same Poisson distribution for the incident rates as in the disutility model, Erkut and Ingolfsson (2000) proposed a risk model that takes into account both the expected value and variance of the number of people affected by an incident. Using the same definition of X_i, N_i, and c_i, and assuming that a single trip can result in several incidents (i.e., the approximate model), the expected value and the variance of $X(P)$, the total number of people affected by incidents caused by travel along P, are $E[X(P)] = \sum_{i=1}^{n} c_i p_i$ and $Var[X(P)] = \sum_{i=1}^{n} c_i^2 p_i$. The associate exact models are $E[X(P)] = \sum_{i=1}^{n} c_i r_i$ and $Var[X(P)] = \sum_{i=1}^{n} c_i^2 r_i - \left(\sum_{i=1}^{n} c_i r_i \right)^2$, where r_i are defined as in (3.14). One can consider these two measures $E[X(P)]$ and $Var[X(P)]$ simultaneously in a multiobjective model and search for paths that are Pareto-optimal with respect to both $E[X(P)]$ and $Var[X(P)]$. To deal with the multiobjective model, one can use the weighted sum technique and obtain a disutility model $E[X(P)] + \beta Var[X(P)]$ for a given constant β. By minimizing this for several values of β, several Pareto optimal paths can be found.

Demand satisfaction model

When a hazmat is transported to satisfy a demand (e.g. a shipment of chlorine from a producer to a chemical processing plant), an incident will result in a subsequent shipment. Hence, we must consider the possibility of multiple trips to fulfill the demand. Erkut and Ingolfsson (2005) proposed a simple demand satisfaction model by assuming that an incident will terminate a trip (i.e., referring to exact model) and a new shipment must be arranged to fulfill the demand. The exact probability that transport along a path P results in at least one incident is

$$\overline{p}(P) = 1 - \prod_{i=1}^{n} (1 - q_i)$$

where q_i are defined as in (3.13). By assuming that this probability is independent of any previous trips that were terminated by an incident, then one can consider each trip as a Bernoulli trial, with probability $1 - \overline{p}(P) = \prod_{i=1}^{n} (1 - q_i)$ of success in any given trial. The number of trips required (on the same path) before the first success (i.e., trip arrives at the destination safely) will then follows a geometric distribution with expected value $1 \Big/ \prod_{i=1}^{n}(1-q_i)$. By taking the expected consequence per trip as in (3.12), the expected total consequence from all trips required to fulfill demand is

$$R^{m}(P)=\frac{\sum_{i=1}^{n}\prod_{j=1}^{i-1}(1-q_j)q_i c_i}{\prod_{j=1}^{n}(1-q_j)}$$

$$=\sum_{i=1}^{n} q_i c_i \prod_{j=i}^{n}(1-q_j)^{-1} \tag{3.15}$$

The expression in (3.15) has the following intuitive interpretation: the term $q_i c_i$ is the expected risk associated with traversing edge i once and the term $\prod_{j=i}^{n}(1-q_j)^{-1}$ is the expected number of times that edge i and the subsequent edges on the path must be traversed before the shipment reaches the destination.

3.3.3 Path risk axioms

Now, we will discuss three important axioms which can be used to assess the merits of the different models listed in Table 3.1. Define $v(P)$ to be an evaluation function that operates on path P (such as distance, cost, or risk). Let $\mathbf{P}_1$ denote the set of all paths between an origin O_1 and a destination D_1, and $\mathbf{P}_2$ denote the set of all paths between an origin O_2 and a destination D_2. Let assume that for any $P_1 \in \mathbf{P}_1$ there is $P_2 \in \mathbf{P}_2$ such that $P_1 \subset P_2$.

Axiom 1. *Monotonicity axiom for path evaluation models* (Erkut, 1995):
If a path P_1 is contained in a path P_2, then $v(P_1) \le v(P_2)$.

Axiom 2. *Optimality principle for path selection models* (Erkut and Verter, 1998):
$v(P_2)=\min_{P\in\mathbf{P}_2} v(P) \Rightarrow v(P_1)=\min_{P\in\mathbf{P}_1} v(P)$

For the third axiom, we assume that $v(P)$ is a function of K edge vector attributes $u_k(P)$ of size n, the number of edges in P, i.e., $v(P) = f(u_1(P), \cdots, u_K(P))$. For example, the attributes of any edge in P can be the incident probability and its associated consequence. In this case, we have $K = 2$.

Axiom 3. *Attribute monotonicity axiom* (Erkut and Verter, 1998):

If h_k, $k = 1, \cdots, K$ are nonnegative vector of reals of size n, then

$$f(u_1(P), \cdots, u_K(P)) \leq f(u_1(P) + h_1, \cdots, u_K(P) + h_K)$$

The first axiom implies that the evaluation value of a path will not decrease as edges are added to the path. Clearly additive value functions (e.g., distance, cost, travel time) satisfy this monotonicity axiom. The second axiom is merely a restatement of Bellman's optimality principle that implies a concatenating property of the shortest path. That is, all subpaths of an optimal path should themselves be optimal. Evaluation functions that satisfy Axiom 2 are called *order-preserving functions*. The third axiom states that the path evaluation function is a non-decreasing function of edge attributes. Consequently, path risk is a non-decreasing function of edge incident probabilities and edge consequences, i.e., increased probability or consequence on an edge cannot result in reduced path risk.

One of the nine models in Table 3.1, namely the conditional risk model, violates all three axioms. Erkut (1995) and Erkut and Verter (1998) argued that this model has some undesirable properties which make the model inappropriate for planning of hazmat shipments. For example, increasing the accident probability on a link may reduce the conditional risk of a route that includes that link.

We now consider the remaining eight models in Table 3.1. Most of the approximate versions of the models listed in Table 3.1 satisfy all three of these axioms. However, without assumption (3.7) or (3.10), most of the "exact" models containing probabilities do not satisfy the axioms. For example, consider the exact version of the traditional risk model defined in (3.9). One can easily construct a simple example to demonstrate that looping reduces the risk (see e.g., Boffey and Karkazis, 1995, Erkut and Verter, 1998, and Erkut and Ingolfsson, 2005). A loop in hazmat route is clearly undesirable (and indefensible). Therefore when using this exact model one must restrict the feasible set to loopless paths (as in Boffey and Karkazis, 1995). However, if one makes assumption (3.7), looping will not occur. Hence, the approximate version of the traditional risk model does not have the undesirable property of the exact version.

The simple example in Figure 3.11 demonstrates how the exact traditional risk model may result in an indefensible route selection. Node 1 is the origin and Node 4 is the destination. The incident probabilities and consequences are given along the edges.

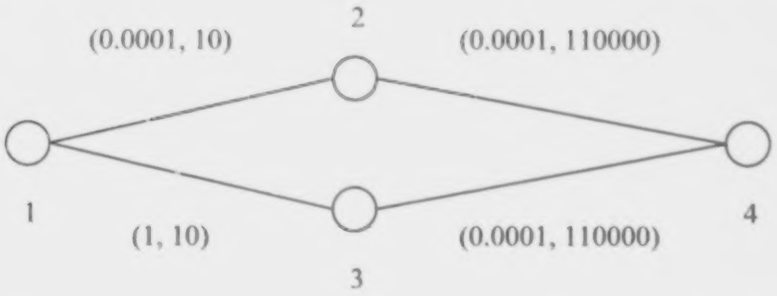


Figure 3.11. Numerical example to demonstrate an undesirable property of the exact traditional risk model.

The exact risks associated with the two paths are as follows:

Path (1, 2, 4): $10^{-4}\times 10+\left(1-10^{-4}\right)\times 10^{-4}\times 110{,}000=10.9999$,

Path (1, 3, 4): $1\times 10+0=10$.

Hence, the exact version of the traditional risk model would select Path (1, 3, 4), and this selection is guaranteed to result in an incident. The downstream consequences on edges (2, 4) and (3, 4) are so high that the model chooses the path which guarantees the truck will not reach the downstream edges. Such a model is not suitable for decision making.

In general, in spite of their more realistic assumption (i.e. an incident will terminate the trip) most of the exact versions of risk models have some puzzling properties and they may be unsuitable for hazmat transportation planning. We suggest that researchers and practitioners consider the properties of the risk models carefully before selecting one.

4. Routing and scheduling

Routing hazmat shipments involves a selection among the alternative paths between origin-destination pairs. From a carrier's perspective, shipment contracts can be considered independently and a routing decision needs to be made for each shipment, which we call the *local route planning* problem. A shipment typically involves multiple vehicles that have to be scheduled. Since the risk factors pertaining to each alternative route (such as, accident probability and population exposure) can vary with time, the vehicle routing and scheduling decisions are intertwined, which we call the *local routing and scheduling problem*. At the macro level, hazmat routing is a "many to many" routing problem with multiple origins and an even greater number of destinations (List and Abkowitz, 1986). In the sequel, we refer to this problem as *global route planning*.

The local routing problem is to select the route(s) between a given origin-destination pair for a given hazmat, transport mode, and vehicle type. Thus, for each shipment order, this problem focuses on a single commodity and a single origin-destination route plan. Since these plans are often made without taking into consideration the big picture, certain links of the transport network tend to be overloaded with hazmat traffic. This could result in a considerable increase of accident probabilities on some road links as well as leading to inequity in the spatial distribution of risk. Although large-scale hazmat carriers are known to consider transport risk in their routing and scheduling decisions (Verter and Erkut, 1997), transport costs remain as the carriers' main focus.

In contrast, the government (municipal, state/provincial, or federal) has to consider the global problem by taking into account all shipments in its jurisdiction. This leads to a harder class of problems that involve multicommodity and multiple origin-destination routing decisions. In addition to the total risk imposed on the public and environment, a government agency may need to consider promoting equity in the spatial distribution of risk. This becomes crucial in the event that certain population zones are exposed to intolerable levels of risk as a result of the carriers' routing and scheduling decisions. The governments' task is further complicated by the need to keep the transport sector economically viable—despite the regulations to ensure public safety—since dangerous goods shipments are an integral part of our industrial lifestyle.

Hazmat local route planning has attracted the attention of many OR researchers. The existing local route planning models cover a wide area that includes different transport modes: road (e.g. Akgün *et al.*, 2000; Kara *et al.*, 2003), rail (e.g. Glickman 1983; Verma and Verter, 2005), water (e.g. Iakovou *et al.*, 1999; Iakovou, 2001); deterministic (e.g. Batta and Chiu, 1988; ReVelle *et al.*, 1991) or stochastic models (e.g. Miller-Hooks and Mahmassani, 1998; Erkut and Ingolfsson, 2000); and single objective (Erkut and Verter, 1998; Erkut and Ingolfsson, 2005) or multiple objective models (e.g. Sherali *et al.*, 1997; Marianov and ReVelle, 1998). Table 2.1 provides a more complete list of references.

The local routing models fail to capture the dynamic nature of transport risk factors at the tactical level (e.g., traffic conditions, population density and weather conditions). Moreover, most of these risk factors cannot be known *a priori* with certainty. They are both time-dependent and stochastic in nature; i.e., they are random variables with probability distribution functions that vary with time. Therefore, the local routing and scheduling problem is best modeled as a path selection problem in a *stochastic time-varying* network (see, for example, Hall 1986; Fu and Rilett 1998; Miller-Hooks and Mahmassani 1998; Miller-Hooks 2001).

The global route planning problem has attained relatively little attention in the literature, much less compared to the local route planning problem. The results in this area include the works of Gopalan *et al.* (1990b), Lindner-Dutton *et al.* (1991), Marianov and ReVelle (1998), and Iakovou *et al.* (1999). The works of Akgün *et al.* (2000) and Dell'Olmo *et al.* (2005) on the problem of finding a number of spatially dissimilar paths between an origin and a destination can also be considered in this area.

The rest of this section provides a discussion on the known models and solution algorithms pertaining to the three problem categories discussed above.

4.1 Local routing problems

As we have discussed in Section 3, almost all approximate versions of the path evaluation functions listed in Table 3.1 are additive and satisfy the optimality principle (i.e., Axiom 2). Therefore, the static, deterministic and single objective local routing problems that minimize those evaluation functions reduce to the classical shortest path problem. Consequently, a label-setting algorithm (e.g., Djikstra's algorithm) can simply be applied to find an optimal route.

Most of the exact versions of these path evaluation functions, on the other hand, do not satisfy Axiom 2. Therefore, Djikstra's algorithm cannot be applied directly to find an optimal route. Kara *et al.* (2003) proposed a simple modification of Djikstra's algorithm to find a route that minimizes the exact version of the path incident probability. The modification relies on the adjustment of the link attribute that is used to update the node label and the scanning process. The algorithm is called the *impedance-adjusting node labelling shortest path algorithm* and is explained briefly as follows. Let $P = \{(i_1, i_2), (i_2, i_3), \cdots, (i_{n-1}, i_n)\}$ with i_1 the origin node and i_n the destination node, and let $q(i_k)$ denote the probability of safely arriving at node i_k of P. From (3.9), we obtain $q(i_k) = q(i_{k-1})(1 - p_{i_{k-1}i_k})$ for $k = 2, \cdots, n$, where $p_{i_{k-1}i_k}$ denotes the incident probability of (i_{k-1}, i_k) and $q(i_1) := 1$. The attribute a_{ij} of each link (i, j) is defined as $a_{ij} := q(i)p_{ij}$. During the scanning process of node i, a_{ij} for each (i, j) is recomputed. This new value is used to update the node label θ_j of node j. If the current value of θ_j is greater than $\theta_i + a_{ij}$, then we set $\theta_j := \theta_i + a_{ij}$, $q(j) := q(i)(1 - p_{ij})$ and update the predecessor of node j. This modified algorithm has the same computational complexity as that of Djikstra's. Kara *et al.* (2003) also proposed the *impedance-adjusting link labelling* algorithm to minimize the path population exposure. This algorithm eliminates the errors resulting from double-counting of population exposure, which is caused by the network topology. Using a similar modification technique to the *impedance-adjusting node labelling shortest path algorithm*, Djikstra's algorithm can be used to solve the local routing problem with the exact version of perceived risk, the expected disutility, and the mean-variance path evaluation functions.

4.1.1. Rail transport

A significant majority of the literature on hazmat routing focus on road shipments. This is not surprising, since trucks account for the largest percentage of hazmat shipments, as discussed in Section 1. Although train shipments can reach comparable levels to truck shipments from a total tonnage perspective (particularly in Europe and Canada), they received considerably less attention from researchers. Remarkably, the literature on marine, air, and pipeline transport of dangerous goods is in its infancy. McClure *et al.* (1988) pointed out a number of differences between rail and highway routing of hazmat transportation. Rail infrastructure is typically owned and maintained by private rail companies. Consequently, railroad networks are sparse and do not contain as many potential alternative routes as highway networks. More importantly, railroads do not have tracks circumventing major population centers that are comparable to interstate beltways around metropolitan areas. A given shipment is likely to be handled by more than one railroad carrier, whereas truck shipments are usually limited to a single company. The rail carriers are motivated to maximize their portion of the movement. In a recent paper, Verma and Verter (2005) highlighted additional differences between the two transport modes. A train usually carries non-hazardous and hazardous cargo together, whereas these two types of cargo are almost never mixed in a truck shipment. Furthermore, a rail tank car has roughly three times the capacity of a truck-tanker (80 tons and 25-30 tons respectively) and the number of hazmat railcars varies significantly among different trains. Another important characteristic of trains is the possibility of incidents that involve multiple railcars. Verma and Verter (2005) noted that there is an average of about one major railroad accident per year during the 1990-2003 period in the United States. Thus, there is a need for the development of risk assessment and routing procedures that incorporate the differentiating features of railroad hazmat shipments.

The academic literature has mostly focused on the comparison of rail and road from the viewpoint of hazmat transport risk. For example, Glickman (1988) observed that the accident rate for significant spills (when release quantities exceed 5 gallons or 40 pounds) is higher for truck tankers than for rail tank cars and that rail tank cars are more prone to small spills. Saccomanno *et al.* (1989) showed that the safer mode varies with the hazmat being shipped and differing volumes complicate comparison between the two transport modes. Leeming and Saccomanno (1994) reported that although hazmat railway shipments pose more risk to residents in the vicinity of railroad tracks, the total risk of these two transport modes does not differ significantly. Their conclusion is based on a single case study in England. In summary, there is no consensus among researchers with regards to the dominant transport mode in terms of public and environmental safety.

Over the past three decades, railroad industry has focused on reducing the frequency of tank car accidents as well as the likelihood of releases in the event of an accident – rather than routing and scheduling of trains with potentially hazardous cargo. The industry's most recent initiatives have aimed at improving tank-car safety at the design stage. By studying the risks associated with non-pressurized materials, Raj and Pritchard (2000) report that the DOT-105 tank-car design constitutes a safer option than DOT-111. Barkan *et al.* (2000) showed that tank-cars equipped with surge pressure reduction devices experienced lower release rates than those without this technology. Barkan *et al.* (2003) undertook a study to identify proxy variables that can be used to predict circumstances most likely to lead to a hazmat release accident. They concluded that the speed of derailment and the number of derailed cars are highly correlated with hazmat release.

4.2 Multiobjective approaches to local routing

As discussed in Section 1, hazmat transportation is *multiobjective* in nature with multiple stakeholders. In general, there is no solution that simultaneously optimizes all the conflicting objective functions in a multiobjective problem. Instead, a set of *nondominated* solutions (or *Pareto optimal* solutions) can be determined. A Pareto optimal solution is one where we cannot improve on an objective without worsening at least one other objective. Local route planning often involves finding the set of Pareto optimal routes between a given origin-destination pair. In the event that the decision maker's preferences among the conflicting objectives are available in advance, the problem can be reduced to a single objective optimization problem (via utility theory).

The *most preferred solution* can then be identified among the Pareto optimal solutions so as to maximize the preference function of the decision maker.

Nembhard and White (1997) considered the problem of determining the most preferred path that maximizes a multi-attribute, non-order-preserving value function both with and without intermediate stops. For the no-stop case, the problem is solved approximately by applying the dynamic programming algorithm as if a sub-path of an optimal path were always optimal (i.e., by using an approximate method on the exact problem). The intermediate-stop case is solved approximately by approximating the non-order preserving criterion with the linear order-preserving criterion and by properly applying the dynamic programming algorithm (i.e., by using an exact method on the approximated problem). Marianov and ReVelle (1998) proposed a linear optimization model to find the routes that minimize both the cost and the exact version of the probability of accident. The weighted sum technique is used to solve the biobjective problem and to approximate the set of Pareto optimal routes. The associated weighted, single objective problem can thus be solved by simply applying the classical shortest path algorithm. Tayi *et al.* (1999) dealt with the cost equity and feasibility problem in hazmat routing, where each edge of the network is associated with a vector of costs incurred by different zones due to an accident along that edge. The zones represent the community clusters, and each component of the cost vector represents the impact of an accident on a zone. The notion of cost equity is represented by six objective functions, including minimization of the average cost path, the maximum cost path, and the imbalanced cost path.

As discussed earlier, many transport risk factors involve considerable *uncertainty*, which increases the difficulty of routing decisions. Two methods that are frequently used in incorporating uncertainty are *mean-risk* (e.g. Markowitz, 1987; Ogryczak and Ruszczynski, 2002) and *stochastic dominance* (e.g. Yitzhaki, 1982; the survey by Levy, 1992). The mean-risk criterion is based on comparing only two values: the mean, representing the expected outcome; and the risk, a scalar measure of the variability of outcomes (e.g. variance and semivariance). Mean-variance (MV) criterion is probably the most well known mean-risk criterion. It states that if $E(v(P_1)) \le E(v(P_2))$ and

$Var(v(P_1)) \leq Var(v(P_2))$ with at least one strict inequality, then $v(P_1)$ is MV-strictly smaller than $v(P_2)$, where $v(P)$ is an evaluation function that operates on path P.

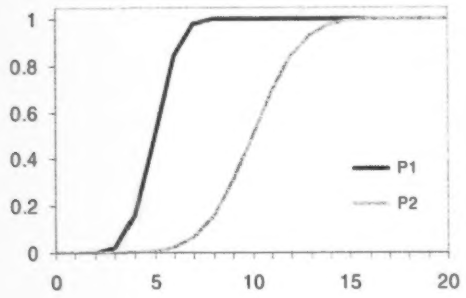
Stochastic dominance (SD) criterion, on the other hand, considers the entire probability distribution rather than just the two moments. It uses the cumulative distribution function (CDF) as a basis for comparison. Let F_{P_1} and F_{P_2} be the CDFs of two random variables $v(P_1)$ and $v(P_2)$. The first and second order stochastic dominance (FSD and SSD) are defined as follows. A random variable $v(P_1)$ is strictly smaller, with respect to FSD, than a random variable $v(P_2)$, if $F_{P_1}(t) \geq F_{P_2}(t)$ for all values of t, and at least one of the inequalities holds strictly. If two CDFs do not intersect, then one of them should stochastically dominate the other, regardless of their variances. Furthermore, a random variable $v(P_1)$ is strictly smaller, with respect to SSD, than a random variable $v(P_2)$, if $\int_{-\infty}^{t} (F_{P_1}(\omega) - F_{P_2}(\omega)) d\omega \geq 0$ for all values of t, and at least one the inequalities holds strictly. For SSD, the two CDFs may intersect, but the total accumulated area between F_{P_1} and F_{P_2} must stay nonnegative up to any t. FSD implies SSD but not vice versa.

Figure 4.1a shows that the distribution F_{P_1} is above distribution F_{P_2} everywhere, and therefore, the probability of "*t or less*" is higher under F_{P_1} than F_{P_2}. In Figure 4.1b, if the two distributions cross within the range of t, then the FSD does not hold, but SSD holds. Figure 4.1c shows that $v(P_1)$ is neither FSD nor SSD smaller than $v(P_2)$ and vice versa. Mean-variance criterion offers a much simpler computational tool than SD criterion. However, a Pareto optimal solution with respect to the MV criterion may be stochastically dominated by other feasible solutions if the normality of distributions is not guaranteed (see e.g. Yitzhaki, 1982; Ogryczak and Ruszczynski, 2002). On the other hand, as the CDFs of $v(P_1)$ and $v(P_2)$ (or their integration) have to be compared for every t, the stochastic dominance itself is actually a multiobjective model with a continuum of criteria. The stochastic dominance criterion usually leads to large efficient sets, and it does not provide us with a simple computational tool.

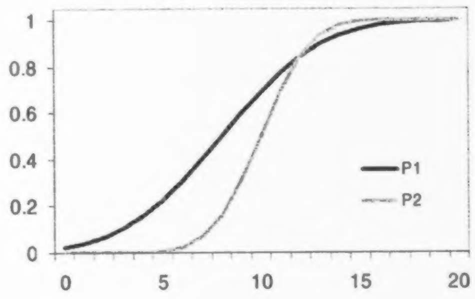
The problem with the efficient set becomes worse in the multiobjective routing problem, as the number of Pareto optimal solutions can be exponential in the number of nodes (Hansen, 1980). To reduce the size of this efficient set, Wijeratne *et al.* (1993) proposed a two-stage evaluation procedure for normally distributed path evaluation functions. This procedure includes a probability parameter that allows the analyst or the decision maker to control the degree to which a comparison deviates from the FSD criterion. That is, a path P_1 dominates P_2 if either of the following occurs:

- *Primary comparison rule*: both the mean and the variance of $v(P_1)$ are smaller than those of $v(P_2)$ (i.e., MV criterion)
- *Secondary comparison rule*: the mean of $v(P_1)$ is smaller, the variance of $v(P_2)$ is smaller, and the CDF of $v(P_1)$ exceeds the CDF of $v(P_2)$ for probability values greater than $(1-q_0)$

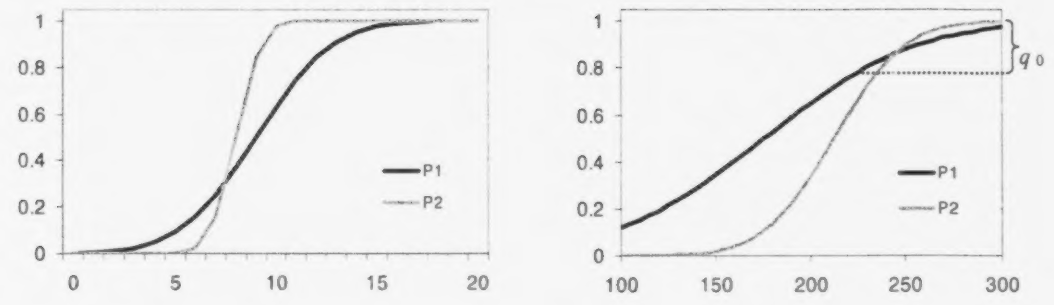
The higher the value of q_0, the smaller the size of the efficient set. However, a small set may exclude some interesting Pareto optimal paths. Consider the following small example. Suppose there are two paths P_1 and P_2 from an origin to a destination, where the mean and standard deviation of $v(P_1)$ and $v(P_2)$ are $(176;64)$ and $(213;30)$, respectively. Figure 4.1d shows that MV and FSD criteria do not hold. By applying the criterion of Wijeratne *et al.*, path P_1 will dominate P_2 for $q_0 > 0.1382$.



(a)



(b)



(c) (d)

Figure 4.1. (a) P_1 is FSD P_2 ; (b) P_1 is not FSD P_2 but P_1 is SSD P_2 ;

(c) P_1 is not SSD P_2 and vice versa ; (d) P_1 dominates P_2 for $q_0 \geq 0.1382$.

Although the example involves a single evaluation function $v(P)$, observe that the incorporation of uncertainty results in a multiobjective problem. Wijeratne *et al.* (1993) proposed a simple procedure to deal with a stochastic multiobjective routing problem (or with a mixture of deterministic and stochastic path evaluation functions). We illustrate this procedure by a small example. Suppose that there are two stochastic path evaluation functions $v_1(P)$, $v_2(P)$, one deterministic path evaluation function $v_3(P)$ (all of these functions are to be minimized) and 4 paths to be compared. Hence, the set of feasible paths is $\mathcal{P} = \{P_1, P_2, P_3, P_4\}$. The comparison is done separately for each evaluation function, where the user-controlled probability parameter q_0 may be different for each stochastic evaluation function. Suppose we find (after applying the two-stage evaluation procedure) that with respect to $v_1(P)$, the set $\mathcal{P}$ can be partitioned into a ranked set $\mathcal{P}^1 = \{(P_1), (P_2, P_3), P_4\}$, which means P_1 dominates all other paths, P_2 is indifferent to P_3, and both P_2 and P_3 dominate P_4. Furthermore, with respect to $v_2(P)$, the set $\mathcal{P}$ may be partitioned into a ranked set $\mathcal{P}^2 = \{(P_1, P_3), P_4, P_2\}$. Suppose that $v_3(P_1) = 100$, $v_3(P_2) = 150$, $v_3(P_3) = 50$, and $v_3(P_4) = 100$, resulting in $\mathcal{P}^3 = \{P_3, (P_1, P_4), P_2\}$. We can thus combine the relative ranking for each path to create a ranking vector of evaluation functions for each path: Path P_1: $(1,1,2)$; Path P_2: $(2,3,3)$; Path P_3: $(2,1,1)$; Path P_4: $(3,2,2)$. (For the deterministic evaluation function, one may put its value, instead of the relative ranking directly in the ranking vector.) The final step is to examine this set of ranking vectors to eliminate the dominated paths. If we require strict dominance across all evaluation functions, we obtain two Pareto optimal routes: P_1 and P_3.

Turnquist (1993) assumed that both accident probability and population exposure are stochastic. He studied the problem of identifying a set of Pareto optimal routes with the following objectives: minimize the incident rate; minimize the population exposed within a certain distance of the roadway; and minimize the travel distance. Turnquist used the distribution functions of each Pareto optimal path on each criterion to highlight the trade-offs among the Pareto optimal solutions.

There are very few static and stochastic routing models (either single or multiobjective) in the literature for hazmat transportation. In addition to Wijeratne *et al* (1993) and Turnquist (1993), the mean-variance model proposed by Erkut and Ingolfsson (2000) is noteworthy. There are static, stochastic path finding models that are designed for other transportation applications (e.g., Frank, 1969; Mirchandani, 1976; Kulkarni, 1986; and Corea and Kulkarni, 1993), which the reader may find useful. Nonetheless, the *dynamic*, stochastic routing is more relevant to hazmat transportation, which we discuss in the next section.

4.3 Local routing and scheduling problems

The traffic conditions and other risk factors in hazmat transportation networks (e.g., incident probabilities and population exposure) often vary with time and can at best be known *a priori* with uncertainty. For example, for a hazmat truck, the travel time and the accident probability on certain road segments can be uncertain and depend on traffic congestion, weather conditions, and road conditions during the vehicle's trip across those links. Hence, the transport risk and arrival time at the destination can vary with the dispatch schedule from the origin. Also, allowing the vehicle to stop during its trip in order to avoid peak risk periods on certain road segments can be an effective strategy to reduce the total transport risk (Erkut and Alp, 2005). To represent this phenomenon appropriately, the transport network should be modelled as a stochastic, time-varying (STV) network.

In an STV network, the link attributes (such as, travel times, incident probabilities, and population exposure) are represented as random variables with *a priori* probability distributions that vary with time. STV network-based modeling has been an important and well-researched topic since the late 1980s (see e.g. Hall, 1986; Fu and Rilett, 1998; Miller-Hooks and Mahmassani, 1998; Miller-Hooks, 2001). Most of the existing results are devoted to the Intelligent Transportation System (ITS), and only some of them are designed specifically for the hazmat transportation problem (e.g. Bowler and Mahmassani, 1998; Miller-Hooks and Mahmassani, 1998). The prevailing studies can be classified into three different groups:

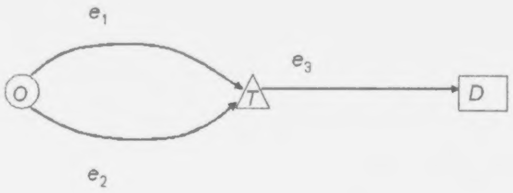
1. *a priori optimization*: the optimal routes are chosen before the travel begins. Hence, an update on the routing decision *en route* is not allowed.
2. *adaptive route selection*: the routing decision is subject to change *en route* based on the realization of the estimated data.
3. *adaptive route selection with real-time updates*: the routing decision is subject to change *en route* due to real-time updates of the traffic data followed by re-optimization procedures.

In the following, we will discuss some of the results in each class that can be applied to hazmat transportation.

4.3.1. A priori optimization

This class of problems assumes that the optimal route is chosen before trip begins. Hence, an update on the routing decision *en route* is not allowed. All routing decisions in static (time-invariant) networks fall into this category.

Hall (1986) showed that in STV networks, one cannot simply set the random arc travel times to their expected values and identify the shortest (expected) travel time by applying standard shortest path algorithms based on Bellman's equation (Bellman, 1958), such as Djikstra's algorithm. The expected travel time on an arc in STV networks depends on the arrival time of the vehicle at the beginning of that arc. A partial route with a higher expected travel time might be selected, if this choice results in a preferable outcome in the rest of the route. This is demonstrated by the numerical example in Figure 4.2.



Arcs	Travel times	Exposed populations
e_1	120 minutes (probability 1.0)	100
e_2	90 minutes (probability 0.3) 140 minutes (probability 0.7)	120
e_3	60 minutes (arrived at node *T* before 16:45) 120 minutes (otherwise)	50 (arrived at node *T* before 16:45) 200 (otherwise)

Figure 4.2. An STV network for the fastest and least risk path problem.

The objectives are to minimize the expected total travel time and to minimize the expected total risk as defined by the expected total number of exposed individuals. Suppose the hazmat truck must leave node *O* at 15:00. On the way to node *T*, arc e_1 has both, the lowest expected travel time, and the lowest expected population exposure (120 minutes and 100 individuals as opposed to 125 minutes and 120 individuals on arc e_2). Hence, Bellman's principle would include arc e_1 in the optimal path. However, note that a vehicle traveling on arc e_2 has a higher probability of arriving at node *T* before 16:45 (0.3 probability as opposed to zero probability on arc e_1). Hence, the total expected travel time and the total expected population exposure via e_2 are lower ($0.3(90+60)+0.7(140+120)=227$ minutes and $0.3(120+50)+0.7(120+200)=275$ individuals as opposed to 240 minutes and 300 individuals).

Hall (1986) proposed an exact, non-polynomial algorithm that combines a branch-and-bound technique with a *k*-shortest paths algorithm to find the fastest path in STV networks. This algorithm, however, applies only to acyclic networks or to cyclic networks with First-In First-Out (FIFO) travel times. (We say that travel times are FIFO if they are nondecreasing functions of time; i.e. if Vehicle A leaves before Vehicle B, Vehicle A will arrive no later than Vehicle B.) Miller-Hooks and Mahmassani (2000) extended Hall's model to allow cycles or non-FIFO travel times. They proposed a time-dependent label-correcting algorithm to solve this fastest path problem. Under the assumption that travel times are continuous functions of time, Fu and Rilett (1998) proposed a heuristic algorithm based on the *k*-shortest path algorithm to solve the fastest path problem without the FIFO assumption. The differentiating feature of their model is the propagation of mean and variance of travel time along a path in the process of determining the fastest path.

Chang *et al.* (2004) adapted the continuous-time mean and variance propagation method of Fu and Rilett (1998) to discrete-time intervals and minimized the total cost as well as the total travel time. The path evaluation functions (except the total travel time) of two paths in STV networks are comparable at a node only if the arrival times of those paths at this node are the same. This condition, however, implies a large efficient set, as it may be unlikely that two paths arrive at a node at precisely the same time. To tackle this problem, Sulijoadikusumo and Nozick (1998) and Chang *et al.* (2004) suggested a time-window criterion: two paths are comparable only if their arrival times are "close enough" as defined by the analyst/decision maker. Suppose Y_i^{Pj}, the arrival time at node *i* along a path P_j, is normally distributed. The probability that the difference of two path travel times is less than or equal to a predefined time window Δ can be approximated as

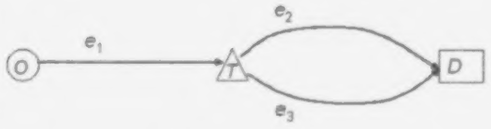
$$p\left(\left|Y_i^{P_1} - Y_i^{P_2}\right| \leq \Delta\right) = \Phi\left(\frac{\Delta - \left(E\left[Y_i^{P_1}\right] - E\left[Y_i^{P_2}\right]\right)}{\sqrt{Var\left[Y_i^{P_1}\right] + Var\left[Y_i^{P_2}\right]}}\right) - \Phi\left(\frac{-\Delta - \left(E\left[Y_i^{P_1}\right] - E\left[Y_i^{P_2}\right]\right)}{\sqrt{Var\left[Y_i^{P_1}\right] + Var\left[Y_i^{P_2}\right]}}\right)$$

where $\Phi(z)$ denotes the cumulative distribution function of a standard normal random variable. If $p\left(\left|Y_i^{P_1} - Y_i^{P_2}\right| \leq \Delta\right) \geq \delta$, where δ is the pre-specified threshold, then these two paths are comparable at node *i*. If the two paths are comparable, then the stochastic comparison methods discussed in the previous subsection can be used to choose the preferred path.

4.3.2. Adaptive route selection

When traveling along a network, the motorist gathers new information that can be useful in making better routing decisions. For example, the arrival time at a node can be used in making a choice among the partial emanating from that node. This is called *adaptive route selection*. The optimal route depends on intermediate information concerning past travel times, road and weather conditions and hence, a single (and simple) path is not adequate.

Hall (1986) showed that the optimal adaptive route in STV networks that minimizes the expected travel time is not a simple path but an acyclic sub-network (called a *hyperpath*) that represents a set of routing strategies (see e.g. Nguyen and Pallottino, 1986). The adaptive route specifies the road link to be chosen at each intermediate node, as a function of the arrival time at the node. As an illustration, consider the example depicted in Figure 4.3.



Arcs	Travel times	Exposed populations
e_1	90 minutes (0.3) 140 minutes (0.7)	100 150
e_2	60 minutes (arrived at node *T* before 16:45) 120 minutes (otherwise)	100 (arrived at node *T* before 16:45) 80 otherwise)
e_3	100 minutes (arrived at node *T* before 16:45) 30 minutes (otherwise)	200 (arrived at node *T* before 16:45) 50 (otherwise)

Figure 4.3. An STV network for the adaptive routing strategy.

The hazmat truck is to leave node *O* at 15:00. The *a priori* expected travel times of two paths $P_1 := \{e_1, e_2\}$ and $P_2 := \{e_1, e_3\}$ are $0.3(90+60)+0.7(140+120)=227$ minutes and $0.3(90+100)+0.7(140+30)=176$ minutes, respectively. The associated *a priori* expected total risks for P_1 and P_2 are $(0.3(100+100)+0.7(150+80)=221$ and $0.3(100+200)+0.7(150+50)=230$ individuals at risk, respectively. Hence, the *a priori* fastest path is path P_2, and the *a priori* least risk path is P_1. However, if the motorist is permitted to select the rest of the path upon arrival at node *T*, we will obtain the following routing strategy:

- Travel time: If the arrival time at node *T* is 16:30, take arc e_2 with a travel time of 60 minutes. If the arrival time at node *T* is 17:20, take arc e_3 with a travel time of 30 minutes. The expected travel time for the adaptive fastest path from *O* to *D* is $0.3(90+60)+0.7(140+30)=164$ minutes. The associated total risk is $0.3(100+100)+0.7(150+50)=200$ individuals at risk.
- Total risk: The routing strategy is the same as for that of the adaptive fastest path.

The resulting hyperpath of the optimal adaptive routing strategy, depicted as a decision tree, is shown in Figure 4.4.

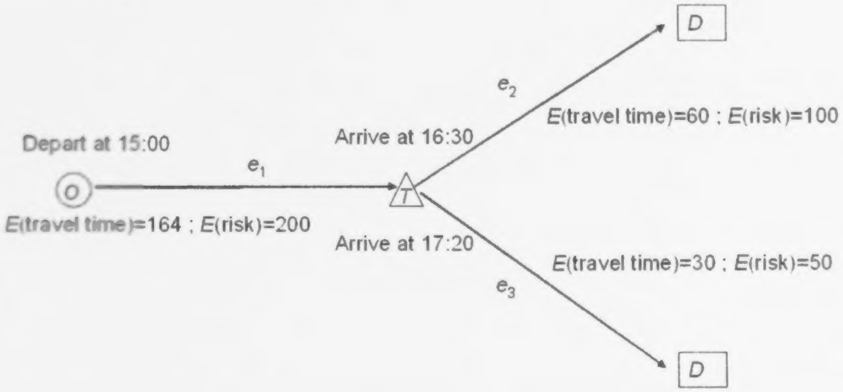

D
e_2
E(travel time)=60 ; E(risk)=100
Depart at 15:00
Arrive at 16:30
e_1
O
T
E(travel time)=164 ; E(risk)=200
Arrive at 17:20
E(travel time)=30 ; E(risk)=50
e_3
D

Figure 4.4. The resulting hyperpath of the adaptive routing strategy, depicted as a decision tree.

It is, in general, quite unlikely that the optimal adaptive routing strategies of different objectives coincide. In this case, the multiobjective version of the label correcting and Stochastic Decreasing Order of Time (SDOT) algorithms from Miller-Hooks (2001) can be used to generate a set of Pareto optimal adaptive routing strategies.

4.3.3. Adaptive route selection with real-time updates

The recent advances in information and communication technologies, such as satellite-based Automatic Vehicle Location (AVL) and mobile phones, enable the driver and dispatch center to obtain and exchange real-time information. Satellite-based AVL is a computer-based vehicle tracking system that uses signals from satellite systems, such as Navstar Global Positioning System (GPS), to identify a vehicle's location. Mobile communication systems such as cellular phones, paging systems, and mobile satellite communication systems, provide two-way communication between the driver and the dispatch center or among drivers. These AVL and mobile communication systems enable the driver and the dispatch center to monitor and/or change the route of vehicles based on real-time information.

These technological advances are challenging OR researchers to develop routing models and robust optimization procedures that are able to respond quickly to changes in the data. In this real-time environment, the quality of the decision depends not only on the appropriateness of the decision, but also on its timeliness (Seguin *et al.*, 1997). Another main issue in this area, besides route planning, is the data updating procedure. New real-time information obtained by the dispatch center is used to update the estimation of future values of some network attributes (e.g., travel times, incident probabilities, and population in the impact area). However, this information is of limited use if the information is about parts of the transport network that are far away from the current location of the vehicle (either spatially or temporally). Therefore, either a spatial or a temporal discounting procedure must be applied before this real-time information is used to update the estimates of network attributes (see e.g. Hoffman and Janko, 1990; Koutsopoulos and Xu, 1993; Yang, 2001).

We observe a lack of papers in this area that consider both adaptive routing decisions and data updates based on real-time information. Moreover, none of the prevailing studies are designed specifically for hazmat transportation problems. Koutsopoulos and Xu (1993) proposed an information discounting procedure for travel times in finding the shortest path in STV networks with a FIFO assumption. For temporal discounting, they used the results from Hoffman and Janko (1990), where the ratio of the historical mean over its current travel time is used to estimate the future travel times on the same arc. Suppose that the route planning is defined in discrete time $\mathcal{T} := \{t_k : k = 0, \cdots, K\}$ with

$t_{k+1} := t_k + \Delta$, $k = 0, \cdots, K-1$. If we denote the travel time ratio on arc (i, j) at time $t \in T^{*}$ by $\delta_{ij,t}$, then

$$\delta_{ij,t} := \frac{\overline{\lambda}_{ij,t}}{\lambda_{ij,t}},$$

where $\overline{\lambda}_{ij,t}$ is the historical average travel time on (i, j) at time t and $\lambda_{ij,t}$ is the associated actual travel time. This ratio is set to 1.0 when real-time information for an arc is not available. To incorporate changes in neighbouring arcs, a smoothed mean ratio is computed as

$$\delta'_{ij,t} := \frac{1}{|A_{ij}|} \sum_{(k,l) \in A_{ij}} \delta_{kl,t},$$

where A_{ij} is a set of all adjacent arcs of (i, j). The new estimated travel time $\lambda'_{ij,t'}$ on arc (i, j) at a future time period $t' = t + \Delta t, \cdots, t_K$ is then given by

$$\lambda'_{ij,t'} := \frac{\overline{\lambda}_{ij,t'}}{\delta'_{ij,t}}.$$

Koutsopoulos and Xu (1993) claimed that actual information obtained on arc (i, j) will be less useful, as either the distance between the origin node and node i increases or the variability of the historical travel time on (i, j) increases. The new estimation of travel time (after being temporally and spatially discounted) on arc (i, j) is

$$\lambda^{*}_{ij,t_0+P_{si}(t_0)} = \overline{\lambda}_{ij,t^{*}} + e^{-\theta\sigma_{ij,t^{*}} \cdot P_{si}(t_0)} \left(\lambda'_{ij,t^{*}} - \overline{\lambda}_{ij,t^{*}}\right)$$

where $P_{si}(t_0)$ is the shortest travel time from the origin node s to node i departing from the origin at time t_0, θ is a positive constant scalar that can be adjusted to produce a good fit between the estimated and actual travel times, $t^{*} - \Delta \le t_0 + P_{ij}(t_0) \le t^{*}$, and $\sigma_{ij,t^{*}}$ is the standard deviation of historical travel time $\overline{\lambda}_{ij,t^{*}}$. The larger the value of $P_{si}(t_0)$ and $\sigma_{ij,t^{*}}$, the larger the discounting of the actual information. This travel time updating procedure is incorporated in the label setting algorithm to find the shortest routes from an origin s. For each arc (i, j) out of the last permanently labelled node i, calculate (if node j is not yet permanently labelled):

$$P_{sj}(t_0) = \min\left\{P_{sj}(t_0), P_{si}(t_0) + \bar{\lambda}_{ij,t^*} + e^{-\theta\sigma_{ij,t^*} \cdot P_{si}(t_0)}\left(\lambda'_{ij,t^*} - \bar{\lambda}_{ij,t^*}\right)\right\}$$

Set the label of a node with the smallest $P_{sj}(t_0)$ to permanent and update its predecessor node, which is needed to construct a path from the origin. The process is repeated until all nodes are labelled permanently.

Yang (2001) discussed an adaptive route selection with real-time updates in discrete STV networks, which is applied to ITS. To update the travel times, Yang considered both spatial and temporal information discounting, which are determined by spatial and temporal depth. The spatial depth determines the maximum reachable distance, with respect to the number of arcs, from the current node. The temporal depth is defined as the maximum number of time periods in which the information is still considered valuable. Furthermore, Yang also proposed two re-optimization algorithms to find the new adaptive route strategy that incorporates the new estimated travel times. The re-optimization algorithms are based on the ELB (Expected Lower Bound) algorithm of Miller-Hooks and Mahmassani (2000) and the SDOT algorithm of Miller-Hooks (2001). These re-optimization algorithms, called "adapted ELB" and "adapted SDOT," assume that the realization of the travel time must coincide with one of the possible values known *a priori*. Hence, it is assumed that the analysts are able to predict all possible values of future travel times, which is not realistic in many cases.

4.4. Global routing problems

The global route planning problem typically belongs to a government agency charged with the management of hazmat shipments within and through its jurisdiction. Although the transportation industry has been deregulated in many countries, hazmat transportation usually remains as part of the governments' mandate mainly due to the associated public and environmental risks. The two main concerns for a government agency are the *total risk* and the *spatial distribution of risk* in its jurisdiction. A number of policy tools are available to the government in mitigating public risk. These include proactive measures such as the establishment of inspection stations (Gendreau *et al.*, 2000), insurance requirements (Verter and Erkut, 1997) and container specifications (Barkan *et al.*, 2000) as well as reactive measures such as the establishment of hazmat emergency response networks (Berman *et al.*, 2005). Another common tool for governments is to ban the use of certain road segments by potentially hazardous vehicles. For an example of such regulation, we refer the reader to the local authority by laws section of the Alberta Dangerous Goods Transportation and Handling Act (Government of Alberta, 2002). In the context of global route planning, the road segments to be closed by the government can be identified by solving a hazmat network design problem, which we discuss in Section 4.4.2 below.

Equity in the spatial distribution of risk can be important for a government agency for two reasons: (i) The perception of risk inequity frequently results in public opposition to the routing of vehicles carrying hazmats through the nearby passageways; and (ii) The overloading of certain road segments with hazmat flows (i.e., risk inequity) may lead to an increase in the incident probabilities as well as the severity of consequences. The concept of equity has been studied in the OR literature primarily within the context of undesirable facility location. Marsh and Schilling (1994) provided a comprehensive review of equity measures for location problems. Erkut (1993) offered two equity axioms for location problems and showed that the Gini coefficient and the coefficient of variation are the only measures that satisfy both of these axioms. Defining n = number of zones, t_i = individual risk at population zone i, and $\bar{t}$ = average individual risk, these two equity measures can be represented as follows:

$$\text{Coefficient of variation} = \frac{\sqrt{\sum_i (t_i - \bar{t})^2}}{n\bar{t}}, \quad \text{Gini coefficient} = \frac{\sum_j \sum_i |t_i - t_j|}{2n^2\bar{t}}.$$

Coefficient of variation evaluates equity in terms of the deviations of the individual risks from the average. In contrast, Gini coefficient focuses on the differences between individual risks. Clearly, smaller values of these equity measures correspond to higher levels of fairness in risk distribution. A value of zero represents perfect equity, whereas a value of one represents absolute inequality. Using GIS, Verter and Kara (2001) estimated these two equity measures for gasoline shipments in Ontario and Quebec under four routing criterion: minimum length, minimum expected risk, minimum population exposure and minimum incident probability.

4.4.1. Equity considerations in global route planning

The multiobjective model proposed by Zografos and Davis (1989) was perhaps the first attempt to explicitly incorporate equity considerations in global route planning for dangerous goods shipments. Their objectives were to minimize the total risk, the risk imposed on special population categories, travel time, and property damage. Equity is achieved by constraining the capacity of the road links. Zografos and Davis used preemptive goal programming in solving the problem, and demonstrated (using hypothetical data) that forcing equity could increase the total risk up to 35%.

Gopalan *et al.* (1990a) proposed an equity constrained shortest path model that minimizes the total risk of travel between and origin-destination pair, while maintaining a desired level of equity among disjoint zones of a transportation network. Each zone constitutes a jurisdiction of a government agency that regulates hazmat transportation. The travel risk associated with road link (i, j) is the sum of risks imposed on the zones in the vicinity of the link. An origin-destination path is considered equitable if the difference between the risks imposed on any two arbitrary zones is under a given threshold. This equitable path definition can be incorporated in the shortest path model through additional constraints. Gopalan *et al.* developed a subgradient algorithm to solve the Lagrangean dual, which is obtained by relaxing the equity constraints. They proposed a labelling shortest path procedure to close any remaining duality gap. The model was applied to a 50-node network from Albany, New York.

Gopalan *et al.* (1990b) extended their earlier work so as to identify a set of routes to be utilized for T trips between a single and origin-destination pair. In this case the equity threshold for a zone pair is the sum of the risk differences over T trips. Note that the T routes do not need to be distinct in their model. Gopalan *et al.* (1990b) proposed a heuristic procedure that repeatedly solves single trip problems using a Lagrangean dual approach with the gap-closing procedure, as in Gopalan *et al.* (1990a). To avoid having T identical routes, the link risks are modified using information from the previous t routes during iteration $(t+1)$. This iterative procedure can easily be adapted to multiple origin-destination pairs.

In extending Gopalan *et al.* (1990b), Lindner-Dutton *et al.* (1991) focused on finding an equitable sequence of T trips, where the cumulative risk incurred by any zone after $t < T$ trips is equitable to that incurred by the other zones in the previous t trips. Both integer programming and dynamic programming (DP) formulations of this problem were presented. Lindner-Dutton *et al.* showed that a DP approach combined with the relaxation and fathoming methods of the Branch and Bound algorithm (as described in Morin and Marsten, 1976) could not solve moderate size problems to optimality within reasonable time. Therefore, they developed five upper bound heuristics to tackle large problems.

Marianov and ReVelle (1998) proposed a linear optimization model to solve the global route planning problem that minimizes both total cost and (the exact version of) accident probability. To introduce equity, they used an upper bound on the total risk associated with each arc. Similarly, Iakovou *et al.* (1999) incorporated equity through the use of a capacitated transport network model. Their multicommodity network flow model has two objectives: minimize transport cost and minimize expected risk cost. They used a weighted sum of these costs in conducting a trade-off analysis. A two-phase solution procedure, similar to that of Gopalan *et al.* (1990a), was proposed. The model was applied to marine transportation of oil products in the Gulf of Mexico.

The studies on generation of a set of spatially dissimilar (not necessarily disjoint) paths are also relevant to equity considerations in global route planning (e.g., Akgün *et al.*, 2000 and Dell'Olmo *et al.* 2005). Iterative penalty method (IPM), gateway shortest paths method, and minimax method are among the procedures that can be used to generate such a set of paths set between an origin-destination pair. However, Akgün *et al.* (2000) showed that the gateway shortest path method may not be suitable for generating dissimilar paths. They posed the dissimilarity problem as a p-dispersion problem (Erkut, 1990). In the p-dispersion context, p of m candidate paths are selected so that the minimum spatial dissimilarity between any pair of selected paths is maximized. The m candidate paths can be constructed using k-shortest path method or IPM.

Erkut and Verter (1998) proposed four indexes to measure the dissimilarity among paths P_1 and P_2 :

- Arithmetic average of two ratios: $1-\frac{L(P_1 \cap P_2)}{2L(P_1)}+\frac{L(P_1 \cap P_2)}{2L(P_2)}$
- Geometric average of two ratios: $1-\sqrt{\frac{L(P_1 \cap P_2)^2}{L(P_1)L(P_2)}}$
- Ratio of the intersection length and the length of the longest path:
  $1-\frac{L(P_1 \cap P_2)}{\max\{L(P_1), L(P_2)\}}$
- Ratio of the intersection length and the length of the union of the two paths:
  $1-\frac{L(P_1 \cap P_2)}{L(P_1 \cup P_2)}$

where $L(P)$ denotes the length of path P.

Dell'Olmo *et al.* (2005) provided a multicriteria formulation of the dissimilar path problem. They used travel distance and transport risk as their criteria. After finding the Pareto optimal set of paths, a buffer zone is constructed for each path in this set. This buffer zone approximates the impact area of a hazmat incident. Based on the buffer zones, a dissimilarity index can be calculated for each pair of paths by replacing $L(P)$ in the above definitions with $A(P)$ that represents the area of the buffer zone around path P. For example, the average arithmetic dissimilarity index can be defined as $1-\frac{A(P_1 \cap P_2)}{2A(P_1)}+\frac{A(P_1 \cap P_2)}{2A(P_2)}$. A subset of maximally dissimilar paths (spatially speaking) can thus be found, for example, by applying the p-dispersion method.

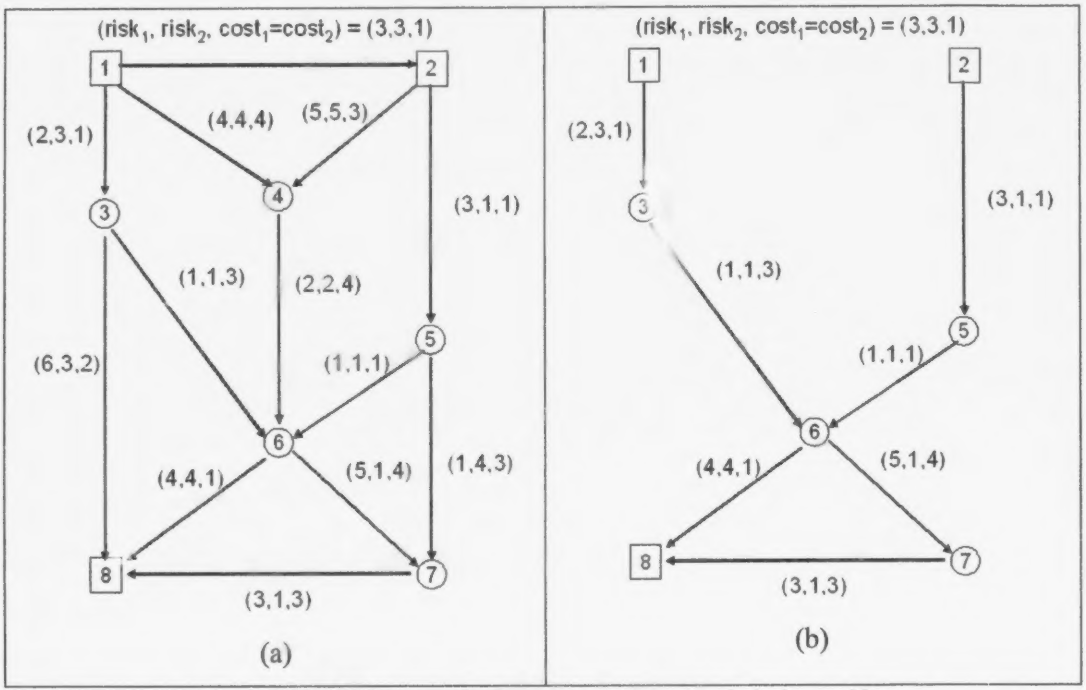
The above models can be useful in identifying a global routing plan for a major hazmat producer/carrier that takes into account the equitable distribution of transport risk in a region. However, these models are of little use in the implementation of a comprehensive global transportation plan in a jurisdiction with multiple carriers since governments have no authority to impose routes on individual carriers. Yet many governments have the authority to close certain road segments to hazmat shipments (permanently or during certain hours of the day), and equity concerns can be incorporated into a hazmat network design problem. This is an interesting and challenging OR problem that has not been studied in the past. In the next section we review a closely related problem: the hazmat network design problem with a risk minimization objective.

4.4.2. Hazmat transportation network design

Network design problems have wide applications in both transportation and telecommunication planning (see e.g. Magnanti and Wong, 1984; Balakrishnan *et al.*, 1997). It is important to recognize the differentiating characteristics of this problem in the context of dangerous goods shipments. The transportation infrastructure is built mainly to connect heavily populated areas and not to avoid them. Therefore, the question becomes which road segments to close in an existing network rather than identifying the most appropriate ways to expand the infrastructure. Kara and Verter (2004) provide the following definition: Given an existing road network, the hazardous network design problem involves selecting the road segments that should be closed to hazmat transport so as to minimize total risk. The carriers will select minimum cost routes on the designated hazmat network, and they are likely to incur higher costs due to reduced availability of routes. Hence, this can be considered a two-level decision problem where the government designates a subset of the transport network for hazmat transport and carriers select routes on this subset.

Note that these two levels cannot be considered in isolation. If one were to select minimum risk routes and offer the union of such routes to the carriers, the carriers would select minimum cost routes on this network which could result in much higher risk levels than the government had intended. This can be illustrated using the example depicted in Figure 4.4a (Erkut and Gzara, 2005). Suppose that hazmat type 1 is to be sent from node

1 to node 8, and hazmat type 2 is to be sent from node 2 to node 8. Assume that the transport cost for each commodity is the same.


(risk$_1$, risk$_2$, cost$_1$=cost$_2$) = (3,3,1)
1
2
(2,3,1)
(4,4,4)
(5,5,3)
4
3
(3,1,1)
(1,1,3)
(2,2,4)
5
(6,3,2)
(1,1,1)
6
(4,4,1)
(5,1,4)
(1,4,3)
8
7
(3,1,3)
(risk$_1$, risk$_2$, cost$_1$=cost$_2$) = (3,3,1)
1
2
(2,3,1)
3
(3,1,1)
(1,1,3)
5
(1,1,1)
6
(4,4,1)
(5,1,4)
8
7
(3,1,3)

(a)

(b)

Figure 4.4. (a) Multicommodity hazmat transport network design problem;
(b) The feasible roads for routing cost minimization.

If the carrier is allowed to route freely, it will select the minimum cost routes $\{(1,3),(3,8)\}$ and $\{(2,5),(5,6),(6,8)\}$ with a total cost of $3+3=6$ units and total risk of $8+8=16$ units. In contrast the minimum risk routes are $\{(1,3),(3,6),(6,8)\}$ and $\{(2,5),(5,6),(6,7),(7,8)\}$ with a total risk of $7+4=11$ units. Figure 4.4b shows the union of the two minimum risk paths. If the government designates this network as the hazmat transport network, but allows the carrier to choose its routes, it will select the minimum cost routes $\{(1,3),(3,6),(6,8)\}$ and $\{(2,5),(5,6),(6,8)\}$ with a total cost of 8 units and total risk of 13 units. This risk is higher than what the government anticipates. As this example demonstrates, the design problem cannot be simplified to a one-level risk minimization problem, and the government must take into account the cost-minimizing behaviour of carriers in designing the network.

The hazmat transportation network design problem has received the attention of researchers only recently. Kara and Verter (2004) proposed a bi-level integer linear programming formulation for this design problem that involves multiple types of hazmats. Their aim is to design a transport network so that the total risk resulting from the carriers' route choices is minimized. At the outer-level, risk is measured as the total number of people exposed to hazmat transport incidents. The inner-level problem represents the carriers' routing decisions on the available transport network so as to minimize their cost. This problem is represented by the linearized *Karush-Kuhn-Tucker* (KKT) conditions of its LP relaxation. As a result, the bi-level integer programming (IP) problem is transformed into a single-level mixed integer programming problem. The proposed model is solved by using CPLEX and applied to the hazmat transport network in Western Ontario, Canada. Kara and Verter demonstrate that carriers can benefit from the government's efforts and involvement in the regulation of dangerous goods shipments.

Erkut and Gzara (2005) considered a bi-level bi-objective (cost and risk minimization) network design problem similar to that discussed by Kara and Verter (2004). They proposed a heuristic algorithm that exploits the network flow structure at both levels, instead of transforming the bi-level IP problem to a single-level formulation. As a result, they achieved a significant increase in the computational performance.

Erkut and Alp (2005) posed the minimum risk hazmat network design problem as a Steiner tree selection problem. This topology takes away the carriers' freedom in route selection and simplifies the bi-level problem to a single level. However, it also results in circuitous (and expensive) routes. To avoid an economically infeasible solution, they suggested adding edges to the Steiner tree. They proposed a greedy heuristic that adds shortest paths to the tree so as to keep the risk increase to a minimum. They also posed a bi-objective version of the problem to minimize cost and risk, and solved it using a weighted additive objective. Their approach allows the decision maker to determine the density of the hazmat network where the options range from a tree to a completely connected network.

Verter and Kara (2005) provided a path-based formulation for the hazardous network design problem. Their main modeling construct is a set of alternative paths for each shipment. This facilitates the incorporation of carriers' cost concerns in regulator's risk reduction decisions. Paths not economically viable for carriers can be left out of the model. Alternative solutions to the network design problem can be generated by varying the number of routing options included in the model. To this end, Verter and Kara use pre-specified thresholds e.g., for the maximum acceptable additional travel distance compared to the shortest path. Therefore, each solution corresponds to a certain compromise between the regulator and the carriers in terms of the associated transport risks and costs. Information about the nature of the cost-risk trade off can facilitate negotiation between the two parties. By using a GIS-based model of Quebec and Ontario, the authors demonstrate that their path-based formulation can be used for identifying road closure decisions that are mutually acceptable.

5. Facility location and transportation

Hazmat shipments often originate from facilities that themselves are potentially harmful to public and environmental safety, such as petroleum refineries or nuclear power plants. Also, the destinations of hazmat shipments can be noxious facilities such as gas stations and hazardous waste treatment centers. The location decisions pertaining to such facilities have a considerable effect on the routing of hazmat shipments. Therefore, integration of facility location and routing decisions can be an effective means to mitigate the total risk in a region where hazmats are processed and transported. It is interesting to note that, in general, location decisions are considered strategic, whereas routing decisions are dealt with at the tactical level. However, the risk constitutes a coupling factor for these decisions in the context of dangerous goods. We refer the reader to Erkut and Neuman (1989) and Cappanera (1999) for extensive surveys of the location-only literature dealing with undesirable facilities. In this section, we provide a review of the prevailing studies on integrated location and routing models for hazmats.

The *location-routing problem* (LRP) involves determining the optimal number, capacity, and location of facilities as well as the associated optimal set of routes (and shipping schedules) to be used in serving customers. The distribution of goods from the facilities to the customers can be on a full-truck load or less than full-truck load basis. In the latter case, routes involving multiple customers are commonly used. From the solution method perspective, the LRP is NP-hard and offers a variety of challenges to OR researchers. The literature addressing LRP with different real-world applications has evolved since the late 1960s. Christofides and Eilon (1969) were among the first to consider LRP with multiple customers on each route. The literature surveys on LRP include Madsen (1983), Balakrishnan, *et al.* (1987), and Min *et al.* (1998).

Two types of risk need to be taken into account in integrating location and routing decisions pertaining to hazmat shipments: transport risk, R^T, and facility risk, R^F. Figure 5.1 illustrates these two types of risk. An individual at point x is exposed to (i) a transport incident on a nearby route segment l of a path P that involves a vehicle carrying volume v_P and (ii) an incident at the hazmat treatment center at site j with capacity u_j. The transport risk, $R_{Pl}^T(v_P, x)$, can be determined as a function of the undesirable consequence at point x, taking into account the impact zone of a hazmat incident on segment l (see Section 3), and the estimated incident probability. The facility risk, $R_j^F(u_j, x)$, can be determined in a similar way, with site j replacing the route segment l. Let **O** and **D** denote sets of origins and destinations, respectively, $\mathbf{P}_{OD}$ denote the set of all utilized paths for each *O-D* pair ($O \in \mathbf{O}$ and $D \in \mathbf{D}$), and **L** denote the set of hazmat facility locations. Assuming additivity of risk, the individual risk at point x can be determined as

$$R(x) := \sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} \sum_{l \in P} R_{Pl}^T(v_P, x) + \sum_{j \in \mathbf{L}} R_j^F(u_j, x)$$

Let A denote the region of interest and *POP(x)* denote the population density at point $x \in A$. The total risk in A is

$$R(A) = \int_{x \in A} R(x) POP(x)\, dx.$$

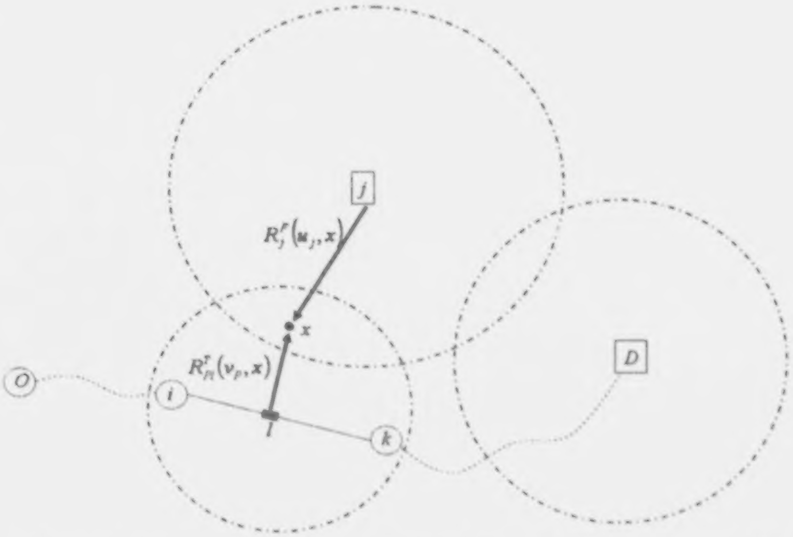


Figure 5.1. Individual risk at point x due to transportation and processing of dangerous goods (adapted from List and Mirchandani, 1991).

Now consider a location-routing problem where $\mathbf{L} = \mathbf{D}$ (e.g., storage locations for spent nuclear fuel shipments). Let V_O denote the hazmat volume at $O \in \mathbf{O}$ (e.g., a nuclear power plant) that needs to be transported, and let u_D denote the capacity of a hazmat treatment facility at site $D \in \mathbf{D}$. Note that $\mathbf{D}$ and $\mathbf{P}_{OD}$ now represent the sets of candidate locations for hazmat treatment facilities and the set of potential paths for each origin-destination pair, respectively. The set $\mathbf{P}_{OD}$ may represent the set of available routes on the hazmat road network designated by the government (see Section 4.4.2). We define two types of variables:

- binary location variables y_D where

$$y_D = \begin{cases} 0 & \text{,if a new hazmat treatment facility is located in site } D \\ 1 & \text{, otherwise} \end{cases}$$

- nonnegative continuous flow variables v_P representing the quantity of hazmat shipped along path P.

Thus, the total risk in region A is

$$R(A) := \int_{x \in A} \left(\sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} \sum_{l \in P} R^T_{Pl}(v_P, x) + \sum_{D \in \mathbf{D}} R^F_D(u_D, x) y_D \right) POP(x) dx$$

In addition to the total risk, the costs (i.e., transportation, operation and fixed costs) should be also minimized. Let c^T_P denote the transportation cost per unit volume of hazmat along path P, c^F_D denote the (annualized) installation cost and c^O_D denote the unit operation cost of a hazmat treatment facility at site D. The total cost, TC, is determined as

$$TC := \sum_{O \in \mathbf{O}, D \in \mathbf{D}} \sum_{P \in \mathbf{P}_{OD}} c^T_P v_P + \sum_{D \in \mathbf{D}} (c^F_D y_D + c^O_D \sum_{O \in \mathbf{O}} \sum_{P \in \mathbf{P}_{OD}} v_P)$$

Also, equity in the spatial distribution of risk due to the location and routing decisions can be a relevant objective. Risk equity can be enforced, for example, by minimizing the maximum individual risk in the region, i.e.

$$\overline{R}(A) := \underset{x \in A}{Max}\, R(x)$$

Hence, a mathematical programming formulation of the capacitated LRP to minimize the total risk and total cost and to force the risk equity can be constructed as follows.

$$\text{Min} \quad R(A) \tag{5.1}$$

$$TC \tag{5.2}$$

$$\overline{R}(A) \tag{5.3}$$

$$\text{Subject to:} \quad \sum_{D\in \mathbf{D}} \sum_{P\in \mathbf{P}_{OD}} v_P = V_O \quad \text{for all } O\in \mathbf{O} \tag{5.4}$$

$$\sum_{O\in \mathbf{O}} \sum_{P\in \mathbf{P}_{OD}} v_P \leq u_D y_D \quad \text{for all } D\in \mathbf{D} \tag{5.5}$$

$$\overline{R}(A) \geq \sum_{O\in \mathbf{O}, D\in \mathbf{D}} \sum_{P\in \mathbf{P}_{OD}} \sum_{l\in P} R^T_{Pl}(v_P, x) + \sum_{D\in \mathbf{D}} R^F_D(u_D, x) y_D \quad \text{for all } x\in A \tag{5.6}$$

$$y_D \in \{0,1\} \quad \text{for all } D\in \mathbf{D} \tag{5.7}$$

$$v_P \geq 0 \quad \text{for all } P\in \mathbf{P}_{OD} \text{ and } O\text{-}D \text{ pairs, } O\in \mathbf{O},\ D\in \mathbf{D} \tag{5.8}$$

Constraints (5.4) ensure that all hazmat generated must be shipped out of the origins, whereas constraints (5.5) stipulate that if a facility at location D is open (i.e., $y_D = 1$), then total quantity of hazmat to be treated at D can not exceed the pre-specified capacity of the facility. Constraints (5.6) are used to incorporate the risk equity. It is evident from the above model that the hazmat LRP is multi-objective by nature. The surveys by List *et al.* (1991), Boffey and Karkazis (1993) and Cappanera *et al.* (2004) observed that literature on hazmat LRP is sparse. In this section, rather than duplicating these surveys, we highlight the important results.

Shobrys (1981) is the first study on hazmat LRP with a focus on selecting routes and storage locations for spent nuclear fuel shipments. A decomposition approach is used to separate the routing problem from the location problem. Two routing objectives are minimized; ton-miles and population exposure-tons. The associated bi-objective shortest path model identifies a set of Pareto optimal paths between each waste source (origin) and each candidate storage site (destination). The weighted costs associated with each

Pareto optimal path determine the cost coefficients of the p-median problem that is used to select the storage site.

Zografos and Samara (1989) considered an LRP with three objectives, namely minimization of transport risk, minimization of travel times, and minimization of disposal risk, to establish locations of a given number of waste treatment facilities and determine the associated shipment routes. Their model requires that the hazardous waste at each population centre must be disposed of entirely. Each population centre is assigned to its nearest disposal facility. Moreover, links of the transportation network are capacitated. Pre-emptive goal programming is used to generate solutions under a few different scenarios.

List and Mirchandani (1991) proposed a hazmat LRP model that simultaneously considers total transportation and treatment risk, total transportation cost, and risk equity. Risk equity is enforced by minimizing the maximum consequence per unit population for all mutually disjoint zones of the transportation network. Their formulation served as a basis for the model in (5.1) – (5.8). However, the List and Mirchandani model is more general since it allows for different types of hazardous materials and treatment technologies. This model assumes that the impact to point x in a zone Z from a vehicle incident is inversely proportional to the square of the Euclidean distance between the vehicle and point x, and the impact is directly proportional to the volume v_P being shipped regardless of material. Hence, the transport risk faced by an individual at point x is determined as

$$R^T_{Pl}(v_P, x) := \alpha v_P \int_{l \in P} \|l - x\|^{-2} c(x) \pi(l) \, dl ,$$

where α is a constant of proportionality, $c(x)$ is a likelihood of impact at point x, and $\pi(l)$ is the probability of an incident at road segment l. The facility risk from an incident at a hazardous waste treatment facility at site j of waste type w with treatment technology t and volume u_{jwt}, $R^F_{jwt}(u_{jwt}, x)$, is determined in a similar way. However, their facilities have unlimited capacity and the total cost of establishing treatment facilities is bounded by a budget constraint. Uncertainty is considered in constructing the risk formulations, but it is not incorporated in solving the example case. Instead, the expected number of fatalities is used to calculate the risk. The LRP problem is solved using LINDO. The weighted sum technique is used to study the tradeoffs among the objectives in identifying the transportation routes, locating the hazardous waste treatment facilities, and choosing the treatment technologies.

ReVelle *et al.* (1991) developed a combined discrete location-routing model for shipments of spent nuclear fuel that minimizes both transportation cost and perceived risk. As in Shobrys (1981), the transportation cost is measured in ton-miles, and the perceived risk is measured using population exposure as people-tons. The total people-ton of an arc is the product of the number of people within a certain bandwidth on the arc and the tons of hazardous waste shipped on that arc. The problem is solved in two stages. In the first stage, a weighted sum of the arc distance and the number of people in the impact area around that arc (called *hybrid distance*) is calculated for every arc in the network. Floyd's shortest path algorithm is used to generate (hybrid) shortest paths for all origin-destination pairs. In the second stage, the location problem is modelled as a *p*-median problem, where the coefficients of the objective function are calculated by taking the product of the tons of spent fuel at the origin and the hybrid shortest distance from the origin to the destination.

Stowers and Palekar (1993) proposed a bi-objective network LRP with a single facility and a single commodity. In a network LRP, the waste facility can be located anywhere on the network. Two objectives are considered, namely minimizing the total exposure (minisum) and minimizing the maximum exposure (minimax). The total exposure to a node or to an arc of the network is represented as a convex combination of location exposure and travel exposure, where the impact area is modelled as a danger circle. Stowers and Palekar showed that an optimal solution to the minisum and minimax problems with only travel exposure occurs at a node. The nodal optimality is still valid for any positive linear combination of travel cost and travel exposure as long as the travel cost is an increasing function of distance, as in ReVelle *et al.* (1991). Moreover, when population is concentrated at nodes only, a finite dominating set of facility locations can be identified which is guaranteed to contain an optimal solution.

Giannikos (1998) proposed a multiobjective model for a discrete hazardous waste LRP that minimizes the following four objectives: (1) total transportation cost and fixed cost of opening the treatment facilities; (2) total perceived risk due to the shipment of hazardous waste; (3) maximum individual risk (to force the risk equity); and (4) maximum individual disutility due to the treatment facilities. The disutility imposed on a population center *i* by the establishment of a treatment facility at site *j* is a function of the capacity of facility *j* and the distance between *i* and *j*. The total disutility at population center *i* is obtained by adding the disutilities imposed upon *i* by all treatment facilities. A weighted goal programming technique is used to solve the problem.

Cappanera *et al.* (2004) presented a single objective LRP model that minimizes the total transportation and facility establishment costs. In their model, an arc formulation is given instead of a path formulation as in (5.1) – (5.8). Their model includes constraints that require both routing and population exposures for each affected site to remain within given threshold values. Arcs of the network are uncapacitated, but the facilities are capacitated. Cappanera *et al.* consider only a single commodity and seek to find the optimal number of facilities. By dualizing the capacity constraints, the LRP is decomposed into location and routing subproblems to obtain a lower bound. To find the upper bounds, two *Lagrangean heuristics*, called the *Location-Routing heuristic* and *Routing-Location heuristic*, are proposed.

In closing this section, we note that almost all existing models for hazmat LRP are static and deterministic. Only the model of List and Mirchandani (1991) considers different types of hazmats and technology selection for hazmat treatment facilities as well as uncertainty in problem parameters. The lack of multiple hazmat models that consider stochasticity in a time-dependent environment constitutes an area for further LRP research.

6. Synthesis and Future Research Directions

To summarize the material we have reviewed, Table 2.1 groups the models into classes distinguished by

- the main aspects of the problem (risk assessment, routing, combined facility location and routing, and network design),
- transport mode
- single vs. multiple objectives
- whether or not stochastic elements are included
- whether or not time-variant elements are included
- whether or not GIS is used

Table 2.1 suggests that the hazmat transportation problems on highways received the most attention from the operations researchers. In contrast, hazmat transportation via air or pipeline, as well as intermodal hazmat transportation has received almost no attention. From the methodological perspectives, we observe that:

- global routing problems on stochastic time-varying networks received no attention despite their relevance and application potential,
- hazmat transportation network design problem which considers all involved parties (government and the carriers) is a relatively young research topic. The most obvious extension of the existing models in this area is to incorporate uncertainty and consider multiple objectives as the hazmat transportation problems are highly stochastic in nature and involve multiple criteria (and players).
- there is an increase on utilizing a GIS either for data input or combined with optimization models to conduct more realistic risk assessment.

Erkut and Verter (1995a) reflected on the state-of-the-art as of 1995, and pointed out a number of directions for future research. In the following ten years, some of the problem areas proposed in Erkut and Verter (1995a) were investigated by researchers, whereas many others remained relatively unexplored. We discuss some of the underexploited areas discussed in Erkut and Verter (1995a), as well as other potential problem areas, that can lead to fruitful research.

Risk calculation—probabilities

QRA relies heavily on empirical accident/incident probabilities. However past data is not very reliable. Using general truck accident data for hazmat trucks overestimates the accident probabilities. What makes matters worse is that there is no agreement on general truck accident probabilities and conflicting numbers are reported by different researchers. Furthermore, applying national data uniformly on all road segments of similar type is quite problematic since it ignores hot spots such as road intersections, highway ramps, and bridges. Researchers need to have access to high quality accident probability data and empirical or theoretical research that leads to improvements in the quality of such data would be welcome.

Risk calculation—perceived risks

Given the limitation of QRA, and the fact that public opposition is a function of perceived risks, perhaps more attention should be paid to quantifying and modeling of perceived risks. We believe more work is needed to improve our understanding of how perceived risks change as a function of the hazardous substance, the distance to a hazardous activity, and the volume of the activity.

Risk calculation—consequences

The second important input in QRA is the population exposed as a result of an incident. Many past studies used uniform population density along transport links which is a very blunt approach. A GIS makes it possible to use more precise population information. However, using census-based population data for daytime hazmat movements makes little sense since census data is residence-based and most residents are not at home during the day. Researchers need to take the next step and incorporate day versus night population distributions, as well as high-density population installations such as schools and hospitals. While this is done relatively easily for QRA of a single route, it is more complicated to generate the necessary data for an entire transportation network.

Risk calculation—time dependence

There are very significant differences in risks between day and night (due to differences in accident probabilities, population distributions, and weather conditions). Yet most of the OR literature pays little attention to this. Risk radii (or safe distances) strongly depend on transport mode and weather conditions. Hence, it is impossible to speak of a single "minimum risk" route; hazmat routing problems must be solved with real-time information. Solving problems with static parameter values can result in poor solutions and decisions.

Risk calculation—model

We emphasized the importance of using the proper risk model throughout the chapter. It is important to use as accurate a model as technically and computationally feasible. For example, it is not only possible, but also necessary to combine GIS data, plume dispersion modeling, and real-time weather information to determine bypass routes for chlorine shipments. In fact, analysis that does not use such level of detail is of little use in the case of hazmats that can generate plumes.

Risk calculation—non-human risks

The vast portion of the hazmat risk literature is concerned with fatalities, and to some extent injuries and property damage. Little if any attention is paid to environmental damage. Environmental risks are usually only included in multiattribute utility models. We believe that hazmat risk models should take into account all risks to humans and environment for broader acceptance by the public.

Multicriteria approach to risk minimization

It is well-known that different routes can emerge as minimum risk routes depending on the definition of risk used. Hence, it is crucial to use multiple measures and provide decision-makers with a set of efficient solutions instead of a single "risk minimizing" route. Development of methodology that would allow for the decision-makers to effectively search the efficient solution set and select a route would be of great practical use.

Risk equity

The academic literature suggests that equity in the spatial distribution of risk is a critical concern in designing hazmat management strategies acceptable to the public. Yet, risk equity is not a great concern to the hazmat industry. If equity is a valid concern then it must be imposed by a regulatory agency.

Local vs. global route planning

Most hazmat transport models deal with only one commodity. While it may make sense for carriers to decompose a transport planning problem into multiple single commodity problems, if one is concerned about concentration and distribution of risks, one has to pose a multicommodity problem where risk and equity concerns couple the different materials. For example hazmat facility location models should include the hazmat distribution network for proper risk assessment. Likewise, the hazmat network design problem requires consideration of all hazmats.

Multidisciplinary nature of the problem

It is rather unfortunate that research in this highly multidisciplinary area continues to be compartmentalized. Chemical and civil engineers tend to publish in their own journals, decision analysts and quantitative risk assessment researchers limit their focus to their paradigms, and operations researchers seldom wonder outside their safe zone. For fruitful research and applications researchers from different disciplines have to reach out to one another.

Cost consequences of risks

One of the reasons why hazmat carriers are not too interested in hazmat routing research is that there are no consequences to not using a decision-support system before making routing decisions. If carriers are faced with lawsuits as a result of poor routing decisions, or if their insurance companies (or creditors) required the use of QRA in route planning to avoid such lawsuits, or if a government agency required the use of QRA and OR tools in route planning, we believe that research in this area would accelerate considerably.

Implementation

It is inconceivable to imagine a hazmat transport DSS that does not take advantage of a GIS while most academic researchers solve small problems on made-up (*realistic*) networks. In fact the ideal hazmat transport DSS would combine GIS, QRA, OR, and MCDA. We suggest that research in this area follow the same recipe. This increases adoption probability by the industry. We note that clever use of GIS can enable one to incorporate non-human risks into the analysis. Another necessary condition for successful implementation of OR research in this area is cooperation between the researchers, the government agencies, and the carriers—something we cannot claim has happened with regularity in the past.

Recent Concern: Security

In addition to the concerns discussed above there is a new concern in hazmat transport planning, namely potential for a terrorist attack on a hazmat vehicle. The terrorist attacks in the USA in 2001 have focused attention on what other targets terrorists may choose. It was quickly recognized that hazmat vehicles could be desirable targets for terrorists, and certain hazmat vehicles were designated as "weapons of mass destruction" (TRB, 2002 and Abkowitz, 2002). Such concerns changed the way the hazmat transport industry operates. For example, the US Federal Government now requires hazmat truckers to submit to fingerprinting and criminal background checks (Glaze, 2003).

This security issue, however. has not yet received much attention from operations researchers. Clearly, the problem is complex and there are many solutions that involve little or no OR. However, there is potential for OR contributions and we list three here:

- Rerouting around major cities: The risk of terrorist attacks made it very undesirable to route hazmat vehicles (particularly trains) through major population centres. Traditional OR algorithms can be used to find alternate routes for shipments. Erkut and Glickman (1997) show that significant risk reductions are possible through rerouting, and Erkut and Ingolfsson (2000) develop new methodology for routing with a catastrophe-avoidance objective.

- Changes in the modeling of incidence risks: The traditional risk assessment for hazmat transport assumes incidents are caused by traffic accidents or human error. Yet we now know that there is a nonzero probability of a terrorist attack or a hijack. Not only does this increase the incident probabilities, but it also requires a new way of modeling consequences since the impact may no longer be limited to the planned route. Furthermore, attack probabilities are unlikely to be uniform. For example, a location in a tunnel, on a bridge, or near a "trophy building" is likely to have a higher attack probability than a location in a remote and unpopulated area. In contrast, sparsely populated areas may be associated with a higher hijack probability. A hijacked vehicle's future route is unpredictable and special precautions may have to be taken to prevent it from having an incident in a highly populated area. As a result, traditional risk assessment-based route planning is no longer adequate. There are very few papers in this new area. (See Paté-Cornell, 2002, for probabilistic modelling of terrorist threats, and Huang and Cheu, 2004 and Huang *et al.*, 2003, for incorporation of security concerns in route planning).
- Changes in route planning methodology: Past hazmat routing literature focuses on finding a minimum risk route. The problem with determining quantitative measures and selecting routes accordingly is that terrorists could predict such routes by using similar methods. To minimize the probability of a successful terrorist attack or hijacking, shippers could alternate routes—game theory can be applied to the problem of alternating among routes to minimize predictability—or change them en-route in real time in ways that would be difficult to predict. Video surveillance or Global Positioning Systems (GPS) and communication equipment installed on all hazmat vehicles would not only allow for precise tracking of vehicles, but also allow the implementation of such real-time decision making (see e.g., Glaze, 2003 and Zografos and Androutsopoulos, 2001).

We believe that there are still many important OR problems in hazmat transportation. However, we think the focus will shift from a priori optimization towards real-time adaptive decision making for several reasons, such as the availability of the necessary technology and data, as well as security concerns. While it is rather unfortunate that terrorist attacks can and do happen, their possibility opens up a new frontier for operations researchers in general, and hazmat transport researchers in particular. We expect that hazmat transport research will intensify in the near future and we hope that this chapter will be useful to future researchers in this area.

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